Integration of Kinesthetic and Tactile Display – A Modular Design Concept

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ABSTRACT

This paper describes the systematic design of a modular setup for several integrated kinesthetic and cutaneous (tactile) display configurations. The proposed modular integration of a kinesthetic display and several tactile displays in serial configuration provides a versatile experimental setup to explore the integration of the kinesthetic and tactile modality of the human perception. The kinesthetic base display is a hyper-redundant device and sufficiently powerful to carry each of the compact tactile displays. In addition to a detailed description of the partly novel displays, a series of preliminary evaluation experiments is presented.

Keywords: haptic, tactile display, kinesthetic display, shear force, slip friction, psychophysics, device-technology

1 INTRODUCTION

Technical realizations of devices to address the haptic modality of human perception can be divided into two main categories, kinesthetic and tactile displays. The two modalities are commonly addressed separately. From the perceptual point of view, this is not the most intuitive way. Simple observations made in everyday life, for example when grasping an object, show that the stimulation of the tactile and kinesthetic perception is often merged to a general haptic experience. For an enhanced psychophysical investigation, as well as for a more realistic presentation of a more extensive (complex) haptic impression, simultaneous stimulation of the tactile and the kinesthetic modality is essential.

Besides the various possible applications in telepresence and VR scenarios, integrated haptic devices also provide a tool to improve the understanding of our kinesthetic and tactile perception from the psychophysical point of view. Several results of investigations in this area indicate that the haptic perception in general implies a strong intercorrelation of tactile and kinesthetic perception.

There are quite few publications about combined tactile/kinesthetic approaches, such as [5] [3] [4]. In brief, the most important drawbacks of previous combined designs are the restricted workspace of the kinesthetic interfaces and insufficient payload of the endeffector, which imposed general restrictions on the design of the tactile display.

The proposed concept envisages a serial connection between a powerful kinesthetic base display, ViSHaRD 10 *(Virtual Scenario Haptic Rendering Device with 10 DOF)*, and several tactile displays. ViSHaRD 10 offers a large workspace due to hyper-redundant joint design. The different configurations are:

- ViSHaRD 10 connected with a novel sphere-based tactile display to provide slip friction.
- ViSHaRD 10 combined with a Shear Force Display.
- ViSHaRD 10 in combination with the VirTouch Mouse, a commercially available computer mouse containing three Braille modules.

Each tactile display is mounted on Vishard 10 via a quick-release fastener, which corresponds to the modular idea. Regarding the control and interface level, both devices are connected via standard LAN connections. This is realized by an enhanced UDP protocol, specialized for telepresence applications. In this manner, the modular concept is realized on the control/interface level as well.

First, a description of the individual single displays is given. This starts briefly with ViSHaRD 10, which plays a key role as kinesthetic base display. After the description of each of the three tactile displays, designated to be mounted on ViSHaRD 10, the corresponding combined hardware setups are presented. Due to the fact that the slip friction display is a novel design and first presented in this paper, it will be described more in detail than the other displays. Finally, preliminary results of psychophysical investigations with two of the three setups are given.

2 DESCRIPTION OF HARDWARE COMPONENTS

This section describes the selected hardware used for the several combined tactile–kinesthetic setups. Except one tactile device (the VirTouch Mouse), all components have been developed and built within the EU-Project TOUCH-HapSys.

2.1 Hyper-redundant kinesthetic display – ViSHaRD 10

As the hand/arm kinesthetic base display component for the integrated device, we designed the hyper-redundant kinesthetic display ViSHaRD 10 [10] to provide spacious force feedback to the operator's hand. ViSHaRD 10 has been developed primarily with the aim to overcome common drawbacks of commercially available systems and create a high-fidelity haptic interface. It provides a large cylindric workspace of $\varnothing 1.7\,\mathrm{m} \times 0.6\,\mathrm{m}$ and a maximum payload of $7\,\mathrm{kg}$, which is sufficient to attach additional haptic displays. In the design, enough space for such a possible display attached to the endeffector has been considered.

Fig. 1 shows the ViSHaRD 10 in ceiling assembly with a cylindric standard grip at the end-effector. Furthermore, it is also possible to mount the display on the floor. In both configurations, the display can provide kinesthetic force feedback in all six possible degrees of freedom of the end-effector, e.g. allowing the operator to interact with a VR scenario as described in [11].

2.2 Sphere-based tactile slip friction display

The influence of forces tangential to the finger tip, so-called shear forces, seems to play an essential role in tactile object exploration. More and more investigations are focused on the characterization and survey of human performance in this issue.

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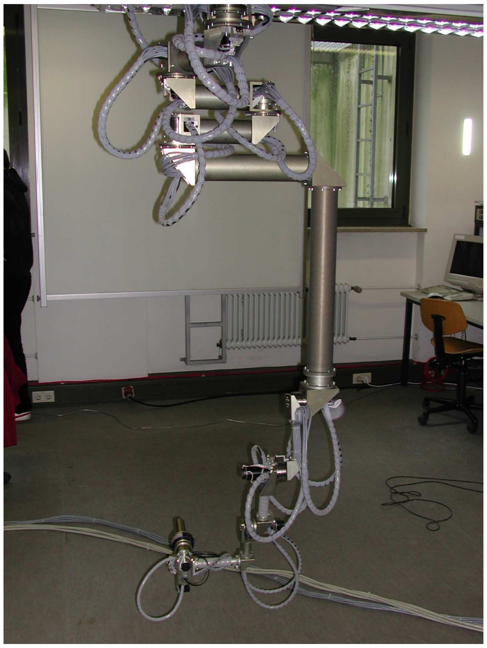


Figure 1: ViSHaRD 10 in ceiling assembly with standard endeffector

General design based on state-of-the-art in slip friction displays

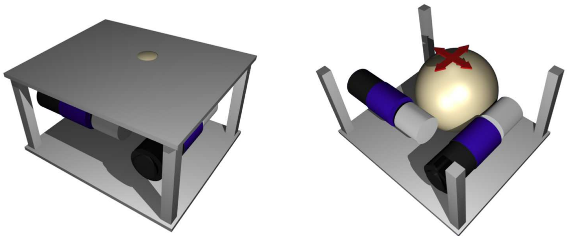
Various kinds of displays have been built to provide shear forces to the human skin, mostly at the fingertip of the index finger. They can basically be categorized in displays using laterally movable pins to induce stimuli, like the one described later in section 2.3, and such using plain movable surface areas analog to the surface they intend to display. The latter kind of displays are normally based on rotating drums [7] or spherical objects [6] [9] [13].

Derived from the general idea of providing a spatial stimulus of slip force caused by lateral friction beneath the index fingertip, we decided to realize the display by using a ball-based design. In contrast to existing sphere-based slip force displays, we are not only interested in high-fidelity, but also in compactness and light-weight design in view of further use in combination with the hyper-redundant kinesthetic display ViSHaRD 10 as a combined kinesthetic – tactile display. In this combination, we plan to validate previous psychophysical findings concerning the perception of superposed tactile and kinesthetic stimuli, especially we are interested in a quantification of the effect of tactile suppression in different configurations.

Previous psychophysical investigations with drum- or sphere-based devices have revealed essential characteristics of human perception. In [9], two experiments have been conducted using highly sophisticated custom-made hardware. The first experiment aimed at determining the JND *(just noticeable difference)* in speed and direction of the perception of slip on two different surface textures. In the second experiment, the relative importance of kinesthetic feedback versus slip feedback in perceiving surface velocity has been investigated. A similar display to the one we intend to build has been used in [6]. It consists of a ball driven by two servo motors, which provides slip forces in both lateral axes to the fingertip of the index finger. This setup has been used to determine the JND of the tactile perception regarding direction sensitivity to a tactile point stimulus that moves across the index fingerpad. However, since this display was designed to be mounted on the endeffector of the comparably small kinesthetic force feedback device PHANTOM, the ball of this display has about half the diameter size of the devices presented above.

Specifications about the maximum curvature of spherical objects to be still perceived as flat surfaces [8] resulted useful to dimension the diameter of the ball of our display. The diameter of a rotating drum of 58.4 mm proved sufficient to create the illusion of a flat surface stimulus. In search of a commercially available ball of this size, we decided to use a billard ball. The chosen white standard ball, usually used by pool billard machines, has a diameter of 60.2 mm.

This ball will be supported by an arrangement of ball-bearings and rotated by two servo motors.



(a) with cover plate (b) without cover plate

Figure 2: Design of the sphere-based tactile slip friction display

Fig. 2(a) presents the setup of the display. The hand of the user needs to be fixed relatively to the device in such a way that the index finger is not mechanically constrained and that the tip of the index finger is in contact with the ball trough an aperture in the cover plate. The dimensions are based on findings in [8], which indicate the optimal aperture size of the casing and the distance between fingertip and the moving part of the device.

Fig. 2(b) provides a view into the inside of the display. Two servo motors are orthogonally arranged, each with a driving wheel attached to its output shaft. These wheels drive the ball in the two lateral axes of motion, thus causing slip friction to the fingertip of the user. As a consequence of the orthogonal arrangement of the driving wheels, each of the two lateral axes can be actuated independently using only one motor. Using both motors in combination, any linear combination of the axes is possible. With this arrangement, a wide range of movement can thus be achieved. Only the rotation of the ball around its vertical axis (z-axis) is not possible, since the axes of the wheels are coplanar and placed at the ball's equator. However, in the intended experiments, this rotational motion can be performed by the supporting kinesthetic device.

The two servo motors used are small DC-motors with a power of 8.7 W each and a maximum speed of 7100 rpm. An attached reduction gear is used to lower the speed by a ratio of $I_1 = 14 : 1$ and to provide a maximum torque of 523 mNm at the output shaft to the driving wheels.

The reduction gear combined with the relation of $I_2 = 4.01 : 1$ between wheel diameter and ball diameter provides a theoretical maximum slip speed of 393 mm/s. The minimum slip speed is constrained by the servo motor controller and thus limited to 0.56 mm/s.

In the experiments, the display shall be mounted on the hyper-redundant kinesthetic display ViSHaRD 10, therefore a compact and light-weight design is essential. With the chosen components as described above, we realized a display with a size of $150 \times 150 \times 150$ mm and a weight of about 1.5 kg.

Hardware setup

The central component of the display is the ball. The standard billard balls we use are made of phenolic resin and come with a polished glossy white surface, which is in general too smooth to be used in our experiments. As the surface is also too regular for the optical position measurement sensor, we made it rougher by sandblasting.


(a) front side (b) back side

Figure 3: Hardware setup of the tactile slip friction display

Fig. 3 shows the hardware setup of the sphere-based tactile slip force display. The front view displays the sandblasted billard ball, which is embedded in the driving unit consisting of servo motors and friction gears. The back view shows the ball ring bearing mechanism of the billard ball in detail.

Each motor driver module includes a closed-loop position/velocity control. It is accessed via a serial RS-232 connection from the operating PC. These driver modules ensure a tracking of the commanded reference position and velocity, and they transmit the measured position and motor current back to the PC.

The current interface receives the position data from ViSHaRD 10 and controls both motors that guide the ball beneath the finger of the operator.

The target is to display a fixed object whose flat surface texture is tactilely explorable by the user. To reach a more accurate measurement of the displayed virtual surface, an additional optical position sensor is planned. This sensor will be placed under the ball directly opposite to the user's fingertip, thus the measured position can easily be mapped to the position of the virtual surface. The sensor has a resolution of 300 dpi, which provides a minimum measurable position resolution of $\Delta x_{min} = 0.085\,\text{mm}$.

2.3 Tactile Shear Force Display

The tactile Shear Force Display is designed with the aim to provide individual force stimuli tangential to the surface of the human skin in the area of the index finger tip. Its fundamental concept is based on a quadratic 2×2 pin array. To exert shear force to the area of the finger tip, each pin is movable laterally to the skin. Thereby it is possible to move each pin independently in both horizontal directions. Design parameters have been chosen based on psychophysical thresholds. A pin diameter of 1 mm, a center-to-center pin spacing of 3 mm (zero position of lateral movement), and a lateral motion of 2 mm along each axis and for each pin have been realized [2].

The mechanical design for one pin and one axis is schematically shown in Fig. 4. The four pins are in direct contact with the finger tip (optionally filtered by an elastic rubber layer). Two rods are orthogonally attached to the upper region of each pin to transmit two-dimensional motion to the pins. In order to allow for this movement, the four pin bodies are attached to the ground plate of the chassis using universal-joint shafts. The rods are connected over reduction rocker arms to the servo motor levers. To decouple the axes of motion between the pin body and the reduction rocker arms, ball joints on both ends of the rods are used. This ensures small backlash.

The actuators are off-the-shelf servo motors, selected based on criteria like high performance, small deviations, and light weight.

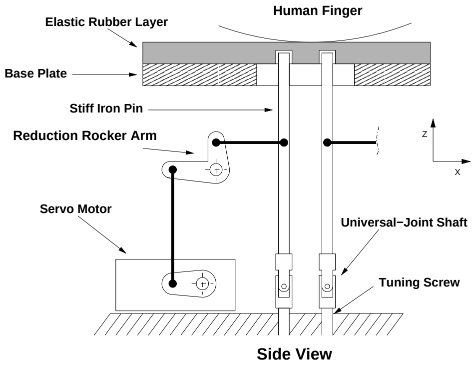


Figure 4: Mechanical design of the tactile Shear Force Display

The servo motors come with a position control circuit, accessed by a pulse-width modulated signal, which contains the commanded position information. The eight actuators are connected to the parallel port of the control PC and the required signals are processed by a real-time thread. In the application process, the position information for the servo motors is calculated and communicated to the real-time thread. In order to ensure that sufficient power for the servo motors is provided, an external power supply is used.

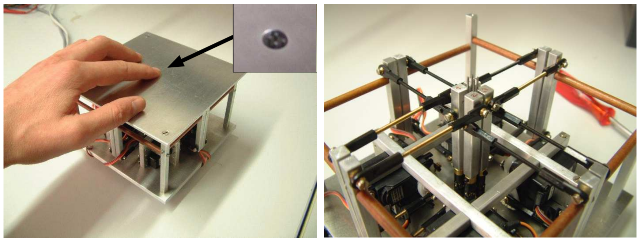


Figure 5: Hardware setup of the Shear Force Display.

The left picture in Fig. 5 shows the display in use with a close-up view of the pin area, which is in contact with the finger tip through a hole in the cover plate. The more detailed view in the right picture of Fig. 5 shows the mechanical details of the display such as the pin bodies, the control rods, and the servo motors.

The Shear Force Display has been used for several psychophysical experiments to investigate the spacial discrimination of angles caused by strokes of tangential pin movements [1]. These investigations have also proved that the realized accuracy in pin positioning is far superior to the requirements posed by human perceptual performance.

2.4 Normal force display – VirTouch Mouse

For its capability of displaying tactile normal force to the fingertip, the commercially available VirTouch Mouse is used. It contains three Braille generator modules for the index, the middle finger, and the ring finger of the operator's hand. The Braille generator modules are integrated in an enhanced computer mouse, connected to the serial port of an ordinary personal computer. Each Braille generator module consists of a dot matrix array in 4×8 configuration. Each of the 96 pins is movable independently in normal direction toward the skin of the operator's finger tip. The range of movement is 1 mm per pin, divided into 16 incremental steps.

Fig. 6 shows the VirTouch Mouse. The close-up view of the Braille module section illustrates the pin arrangement of the Braille units, inserted in the corresponding finger molds. The positions of

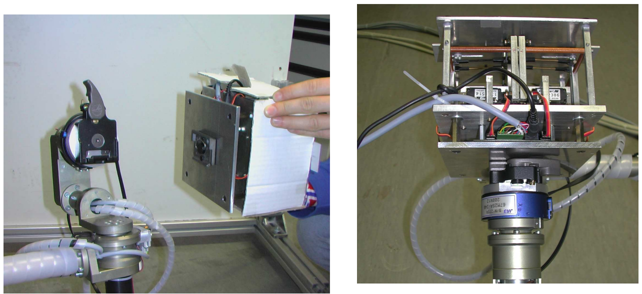
Figure 6: VirTouch Mouse

the pins are guided by bending piezo actuators. The interface, as well as electrical drivers and power supply, is integrated and used as bought without any modifications. However, to use the full functionality of the VirTouch Mouse as a tactile display, the development of a self-made device driver software was necessary. This device driver has been realized as a RTLinux real time module under special privacy conditions from VTS (Virtual Touch Systems) regarding the transmission protocol of the serial link.

3 MODULAR INTEGRATION OF KINESTHETIC – TACTILE HARDWARE

This section starts with a description of the hardware connection mechanism between the kinesthetic base display and the several tactile displays. An important issue during the practical realization is to find a general connection system that allows a fast and simple change of tactile display modules. We realized this by using a quick-release fastener mechanism.

The end-effector of ViSHaRD 10 is connected to the fitting flange located at the upper end of the force/torque sensor. This sensor measures contact forces and torques caused by the interaction of the operator and the virtual environment, transmitted via the device. This connection is realized by a bolted joint, normally not designed for frequent changes of the end-effector. For using ViSHaRD 10 as kinesthetic base display for several additional attachable devices, dependent on the task to perform, we have implemented a quick-release fastener between the force/torque sensor and the additional device to facilitate the changing procedure of the endeffector or other mounted devices.



(a) Quick release fastener

(b) SF-Display attached to ViSHaRD 10

Figure 7: Mounting mechanism on ViSHaRD 10

The left part of Fig. 7(a) shows the base plate of the quick-release fastener with release lever open, fixated on top of the force/torque sensor. In the right part of the picture, the counterpart of the fastener is shown, fixed to the bottom of the tactile Shear Force Display, which has been described above. Regarding the fastener, we chose an off-the-shelf quick-release fastener usually used as photography equipment. In this case, we selected a robust fastener made of metal to ensure a stiff connection between ViSHaRD 10 and the end-effector that is free from backlash.

Fig.7(b) shows the tactile Shear Force Display mounted on the force/torque sensor (blue) via the locked quick-release fastener. The SF-Display is kinetically connected in a serial manner. Thus, with this configuration it is possible to exert tactile shear force stimuli to the finger tip as well as kinesthetic forces to the hand.

3.1 Computer interface

Each of the mounted displays has been developed separately with its own PC-based control system, mainly in Realtime Linux. To use them together as an integrated display, a network concept regarding control and communication between the constituent displays is necessary.

Fig. 8 shows the interconnection between the two display systems. The current control concept for ViSHaRD 10 consists of an admittance control algorithm with quaternion based mapping of the position coordinates [11]. In this control mode, forces are measured and motion is commanded to the display's internal Cartesian position control core. For more detailed explanations about the principles of the possible control schemes, please refer to [12]. The control algorithm has been implemented in a Matlab SIMULINK model. Due to the demand for realtime capability, the controller core is running as a realtime task on a RTLinux based computer (right side). This thread communicates over channel bidirectionally with the necessary hardware components, such as DAC I/O-cards and the force/torque sensor. In addition, this realtime task is connected internally via a fifo (first in first out) buffer communication channel to an application program, which runs on the same computer. The main function of the application is to manage the inter-computer communication over a UDP-socket based LAN connection. The used interconnection method based on UDP-socket connection, developed within the SFB 453 (Collaborative Research Centre 453: High-Fidelity Telepresence and Teleaction), has been generalized and modified for the use with Matlab SIMULINK, for flexible implementation and communication between different devices. Over this connection, the current position and velocity values of the endeffector of ViSHaRD 10 are transmitted. The position control algorithm of the Shear Force Display pins is hosted on an additional computer with a similar software implementation. The application receives the position and velocity information via the UDP-socket connection and calculates the appropriate reference position for the pins of the SF-display. These position coordinates are communicated to the task over a unidirectional fifo buffer connection. The realtime task generates the position signal at the printer port, which supplies the servo motor with the desired reference position.

3.2 Hardware setups

In the following, the three possible hardware setups are presented. The specific setups can be mounted and changed very quickly without much reinitialization or calibration effort. Thus, the modular concept of the components works mostly autonomously and communicates via the UDP-socket based LAN connection described above.

ViSHaRD 10 + Slip friction display

The first setup has been realized by combining ViSHaRD 10 with the tactile slip friction display. Fig. 9(a) shows the slip friction display mounted on ViSHaRD 10 without chassis. It is connected directly through the described quick-release fastener described above.

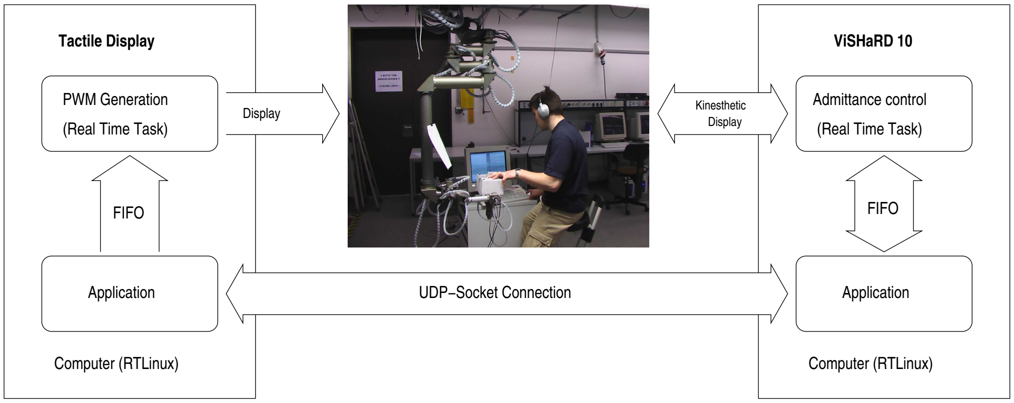


Figure 8: Computer interfaces and inter display connection scheme

(a) Slip friction display (b) Shear Force Display (c) VirTouch Mouse

Figure 9: Tactile displays, mounted on ViSHaRD 10

For later experiments, an additional fixation for the finger will be used.

ViSHaRD 10 + Tactile Shear Force Display

Fig. 9(b) shows the combination of ViSHaRD 10 with the tactile Shear Force Display in floor configuration. It shows the same experiment as Fig. 8, but in Fig. 8 VisHaRD 10 is mounted to the ceiling and in Fig. 9(b) fixed at the floor. Because of the symmetric design, this can easily be realized by modifying some parameters in the control program. The finger of the operator can be connected in a serial, as well as in a parallel manner. For the parallel configuration, the wrist needs to be fixed to the tactile Shear Force Display by an elastic strip. A more detailed view of the mounted Shear Force Display is shown in Fig. 7, which also displays the applied connection mechanism described above.

ViSHaRD 10 + VirTouch Mouse

The third setup combines the VirTouch Mouse (VTM) with ViSHaRD 10. To account for the requirements of modular integration, the VTM is attached to an aluminium plate that contains the counterpart of the quick-release fastener at the bottom of the plate. Fig. 9(c) shows the realization of the combined kinesthetic/tactile setup with the VirTouch Mouse display attached to the endeffector of ViSHaRD 10.

4 PRELIMINARY EVALUATION EXPERIMENTS

With a first series of experiments, we want to find out more about the impact of combined kinesthetic/tactile stimuli during haptic exploration compared to purely kinesthetic stimuli. With this objective, we designed an experiment that can be implemented for all three hardware setups of combined kinesthetic and tactile stimuli that have been presented in this paper. These experiments also offer a means to assess the performance of the individual hardware setups.

For preliminary experiments, we use ViSHaRD 10 in combination with the tactile Shear Force Display and the VTM, respectively. Participants are virtually presented with a wavy surface, which is simulated by combined sinusoidal stimuli. The standard stimulus is provided by ViSHaRD 10 and consist of a sinusoidal kinesthetic stimulus with an amplitude of 1 mm. The wave length of the sine is 10 cm, and the length of the complete virtual surface is 50 cm and constrained to one axis of motion (1 DoF).

To each standard stimulus, an additional set of comparison stimuli, provided by the attached tactile display, is chosen. In the case of the tactile VTM, we display the sinusoidal shape in 10 linearly distributed intensities between 0 and 1 mm, in phase with the standard stimulus. For the Shear Force Display, we graduate the intensity in 5 steps also between 0 and 1 mm. Furthermore, we add a phase lag of 180° compared to the kinesthetic stimulus, because such a phase lag enhances the impression of bumps and holes in the virtual sinusoidal surface.

In each trial, the participants consecutively feel a standard and a comparison stimulus. Then they are asked to decide which of the two stimuli had been more ”realistic”. Each pair of stimuli is presented 20 times. The order of the pairs, as well as the order of presentation of a pair is randomized.

Fig. 10 shows the preliminary results (obtained with three participants) of the combined setup of ViSHaRD 10 and the Shear Force Display. Displayed are mean and standard deviation. These results indicate an enhancement in realism of the impression of up to nearly 100 %. The maximum value is reached at the amplitude of

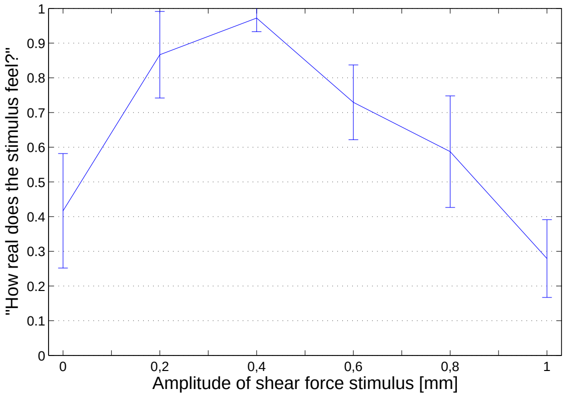


Figure 10: ViSHaRD 10 + Shear Force Display

0.4 mm provided by the Shear Force Display. Interestingly, when the amplitude of the force stimulus is further raised, it starts to feel disturbing. One participant reported that in case of the full excursion of the shear force stimulus, the combined stimulus felt more like two separate stimuli.

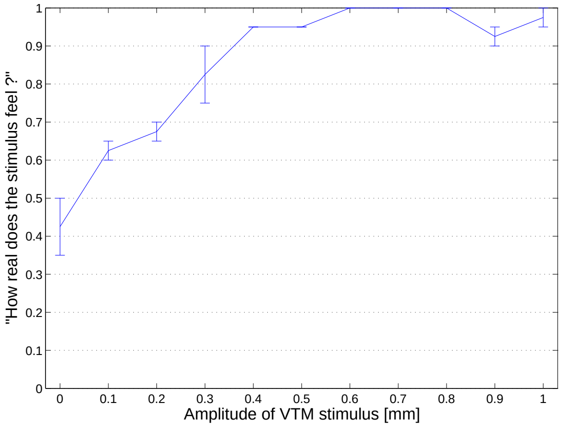


Figure 11: ViSHaRD 10 + VirTouch Mouse

The results of the combination with the VTM are presented in Fig. 11. It has been taken from two subjects and shows the expected trend that an increase of the amplitude of the tactile stimuli normal to the fingertip will also enhance the impression of reality.

5 CONCLUSION

In this paper, a versatile modular concept for several integrated kinesthetic – tactile setups is proposed, each consisting of a kinesthetic base display and one of three different tactile displays. The main attention is on the novel design and setup of a tactile slip friction device. This device complements the hardware setup, which now provides a wide range of possible tactile stimuli.

With this modular concept, systematical investigations regarding the tactile and kinesthetic sub-modalities can be performed. Recent, ongoing and planned experiments that will use the described modular integrated hardware setups include experiments to validate the tactile display quality, and psychophysical experiments concerning the human haptic perception.

The preliminary experiments show promising results towards the evaluation of the several hardware setups and indicate that the hardware framework can be used for a large number of further experiments.

6 ACKNOWLEDGEMENTS

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