Tactile Feedback at the Finger Tips for Improved Direct Interaction in Immersive Environments

Robert Scheibe[1, 2] Mathias Moehring[1] Bernd Froehlich[2]

[1]Volkswagen AG, Group Research [2]Bauhaus-Universität Weimar

Abstract

We present a new tactile feedback system for finger-based interactions in immersive virtual reality applications. The system consists of tracked thimbles for the fingers with shape memory alloy wires wrapped around each thimble. These wires touch the inside of the finger tips and provide an impression when they are shortened. We complement the impression on the finger tips by a subsequent vibration of the wire to generate a perceivable tactile stimulus over a longer period of time. The shortening and relaxation process of the wires as well as the vibration is controlled through a micro-controller receiving commands from the virtual reality application.

We use the tactile feedback for communicating finger contacts with virtual objects in an application prototype for usability and reachability studies of car interiors. Our experiments with the system and an initial pilot study revealed that this type of feedback helps users to perform direct manipulation tasks with more reliability. Our users also preferred the system with tactile feedback over a system without the feedback.

Keywords: Direct Interaction, Tactile Feedback, Shape Memory Alloys

Index Terms: I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism - Virtual Reality B.4.2 [Input/Output and Data Communication]: Input/Output Devices – Channels and Controllers

1 Introduction

The automotive industry performs numerous analyses concerning safety, ergonomics, design, assembly and in many other areas during the development process of new car models. Today hardware models are commonly used for these analyses. The construction of these mock-ups is time-consuming and cost-intensive, their variability is limited. Some of the necessary analyses have the potential to be performed within virtual environments. Virtual models can be directly derived from CAD data and they are therefore available in very early phases of the development process. Variants and modifications can be accomplished easily and tools can be used that are not available in reality, e.g. arbitrary cuts and pseudo-colored visualizations of air flows inside the car.

Figure 1: User interacting with a virtual car interior in the CAVE (left), finger tracking system with our tactile feedback device mounted on the user's hand (right)

robert.scheibe@ar-tracking.de
mathias.moehring@volkswagen.de
bernd.froehlich@medien.uni-weimar.de

The use of virtual environments for ergonomic studies in a car interior is particularly challenging since the realistic interaction with various parts of the interior needs to be supported. We have developed the Immersive Interactive Data Model (I²D) [MF05], which allows users to directly interact with assemblies of the car such as doors, steering wheel, sun visors, etc. Two things are essential for this type of application in a CAVE-like environment: the real hand has to be exactly registered to the virtual hand to allow reachability studies and the users have to be able to recognize collisions of their fingers with virtual objects for reliable grasps and manipulations. However pure visual feedback is often not sufficient and haptic feedback systems are difficult to use in CAVE-like environments.

We developed a tactile feedback system for the finger tips supporting users during direct interaction in immersive environments. The system consists of tracked thimbles for the fingers with thin shape memory alloy wires wound around each thimble (figure 1). The wires can be shortened by slightly heating them up by an electrical current. This effect is used to create an impression on the inner side of the finger tips, where the wires touch the skin of the finger. We use the tactile feedback to report individual finger collisions to the user during an interaction with virtual objects.

The original implementation of our I²D system for ergonomics and usability studies [MF05] combined pseudo-physical interaction with visual user feedback for contact and grasping situations. By observing users we found that two effects make it difficult to judge the fingers' exact position and pose in relation to virtual objects:

- The manipulation of small parts often requires grasps which occlude the manipulated object.
- Users were not able to focus virtual objects located near to the hands. Their eyes alternate between focusing the screen and the hand and thus the two stereoscopic images presented on the screen cannot be converged, the spatial perception gets lost.

These effects can be hardly avoided with projection-based systems. Head-mounted displays are an alternative to avoid the second problem, but according to our experience the acceptance by engineers and designers is very limited. Displaying the virtual hand with a positional offset – a common solution for both problems – as for example suggested by [MBS97] – cannot be used for reachability studies.

The main contribution of this paper is the design, development and evaluation of a set of prototypes for providing tactile feedback at the finger tips. Besides building the actual finger tip actuators, we realized the microcontroller-based driving circuitry and integrated the system with our VR application for ergonomics and usability studies in virtual car interiors. We performed a pilot study comparing the system with and without tactile feedback for various manipulation tasks such as opening and closing the door, operating the light switch, and adjusting the interior mirror. The participants felt much more in control with tactile feedback support. They also reported that this type of feedback at the finger tips matches very well the task at hand.

2 Related Work

The lack of haptic feedback particularly in projection-based immersive environments is one of the main drawbacks of VR. We provide a short overview of the work tackling this problem. Our design relies on the physiological parameters of the fingers' skin as well as the physical properties of shape memory alloys and haptic systems based on these actuators.

2.1 Haptic Feedback in Virtual Environments

Haptic feedback can be differentiated into true force feedback and tactile feedback. Force feedback tries to simulate the real kinesthetic input for users during interaction with virtual objects. Both, research approaches like for example the HapticGEAR [HHO+01] and commercial products, e.g. CyberGrasp™ and Haptic Workstation™ by Immersion Corp. [@IMM], are still of very limited applicability for direct interaction in projection-based virtual environments. The limited working volume and obtrusive design in combination with high installation and maintenance requirements (cf. [RHSM05]) are the main critical issues.

Tactile feedback uses the somatic senses of the skin as a channel to provide information to the user. Research in many different areas has used tactile feedback as an information channel. Examples include the use of vests with integrated actuators as tactile displays [NJ03], sensory substitution devices for helping visually and acoustically impaired people [Bur96], and actuators mounted to input devices [RHSM05] or the users themselves [JG04] for providing motion cues and collision information to the users of VR applications.

Most work relies on vibro-tactile actuators, which are today inexpensive, small and reliable off-the-shelf components. A variety of techniques can be used to generate the vibratory output. Approaches with voice-coils are known as well as the use of piezoelectric elements. [KH95] discusses key issues of this technology.

The CyberTouch™ by Immersion Co. [@IMM] is a commercial solution employing vibro-tactile feedback. This system combines a conventional CyberGlove™ with six vibration motors, one mounted to the upper side of the middle phalanx of each finger and one mounted to the inner side of the palm. The device is used for creating for example contact feedback with virtual objects. However, creating contact feedback at the back side of the finger phalanxes does not seem to be the ideal location, since the contact happens typically at the finger tips. Additionally, the receptive fields responsible for vibration recognition are quite large, leading to unspecific perception (cf. chapter 2.2). The weighty motors in combination with the tight fit of the glove create a relatively high pressure of the actuators on the skin of the fingers, which can lead to a transfer of the vibration output to the bone structure anticipating isolated stimulus perception [BB04]. Other research on using vibro-tactile feedback in VR applications reports little benefit [RHMS05, JG04], which motivated us to seek for other solutions.

Inaba and Fujita [IF06] propose a tactile feedback device concept quite close to ours. A belt wound around each fingertip is tightened by a motor to generate what they call a "pseudo-force-feedback". In contrast to our approach the whole fingertip is used as a display and no further discrimination of haptic patterns is possible. The actuators composed of a belt and a motor for each fingertip do not seem to be lightweight and unobtrusive enough to avoid disturbing the user during interaction.

2.2 Human Haptic Sensory System

The characteristics of the local sensory system have to be taken into account when designing a tactile display for the finger tips. The human skin is interspersed with four different neuronal subsystems. Each of these mechanical-receptive fibers is sensitive to a certain kind of stimulus due to the properties of the receptor cells they consist of. [BHB+95] compares capabilities of the receptors with specifications of – besides others – tactile displays.

Merkel cells detect pressure on or indentation of the skin with high resolution. They slowly adapt to continuous pressure at low frequencies. The first part of our activation pattern (cf. chapter 4) stimulates this cell type.

Vibration is detected by two different kinds of cells. Frequencies below 30 Hz are sensed by Meissner corpuscle. They have a high density on the fingertips and therefore a high spatial resolution. Furthermore they do adapt slowly to a subsequent vibration-stimulus, but they adapt quickly to a subsequent skin indentation. The second part of our activation pattern (cf. chapter 4) stimulates these cells.

Pacinian cells react on vibration with a frequency of more than 200Hz. These cells are not as widespread as the Meissner corpuscle and their spatial resolution is not as high. As the vibration of the SMA actuator is below 200 Hz these cells are not activated.

Ruffini cells are responsible for horizontal displacement at low frequencies and are not stimulated by our system.

Other work refers to slightly different parameters of the four cell types [NJ03, KH95, Gol97] but agree that high frequency vibro-tactile stimuli are perceived by receptive fields that have a large diameter resulting in a JND (Just Noticeable Distance) that makes it impossible to differentiate more than one actuator at the finger tips [KH95].

2.3 Shape Memory Alloys – Effect and Applications

Nitinol is named after the Naval Ordnance Laboratory where the shape memory effect of Nickel Titanium alloys was discovered. Shape memory alloys are characterized by the ability to alter the shape due to temperature changes. These materials have two distinguishable crystalline structures – Martensite, the low temperature state and Austenite, the high temperature state. By heating the material it can be forced to turn to Austenite, while when cooling down, it will return to Martensite. The thresholds of transformation depend on the mixing ratio of nickel and titanium. The conversion is characterized by a hysteresis which means that the thresholds depend on the direction of the transformation (cf. figure 2). The temperature threshold marking the beginning of trans-

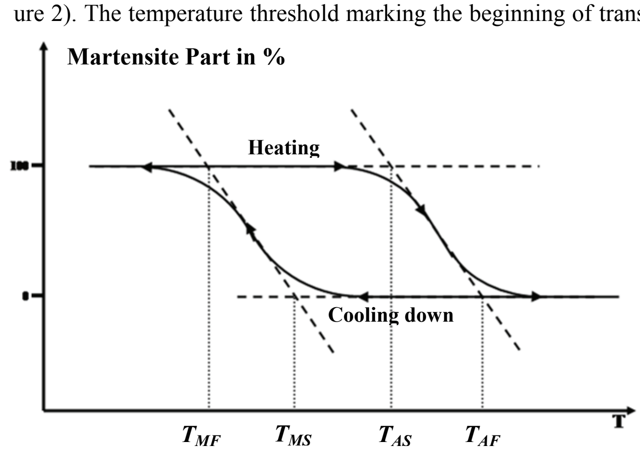

Figure 2: Characteristic Hysteresis Curve of Nitinol

formation to Austenite (Austenite Start T_{AS}) is not the same as the temperature Martensite transformation ends at (Martensite Finish T_{MF}) when coming from high temperature state. This makes it impossible to derive the material state from temperature, making it difficult to build a simple control loop. Objects can be forced to have a certain shape in each state by training them. Shapes can simply be different lengths of a wire for the two states.

There is a trade-off between elongation length and durability of the material. If only one contraction is needed it can provide length changes of up to 8%. For a two-way effect elongations of up to 5% are reported but this comes along with a reduced lifetime of tens of thousands of cycles or less while aiming at durability only around 2% of length change should be trained [NJ03]. Another property of SMAs is pseudo-elasticity, meaning that the object can be deformed and the material returns immediately to the former shape. Here Martensite is built mechanically leading to a strain of up to 8% which is more flexibility than any other metal can provide.

SMAs are well known and have been used in several research projects and commercial products for years. All three properties, the one-way effect, pseudo-elasticity and the two-way effect, are useful for certain requirements. Although there are applications for the one-way effect – e.g. used for pipe connections – and pseudo-elasticity – used with unbreakable glasses frames for example – we will focus on approaches using the two-way effect, since this is needed for a tactile feedback device.

Besides applications in commercial products, e.g. as temperature sensors, there are few other approaches for providing tactile feedback based on shape memory alloys. Arrays of pins used as tactile displays are presented in [WPFH98, VPHS05]. These devices can be attached to input devices to provide additional information. [NJ03] mounted an actuator in a vest which stimulated the user's skin by pins driven by SMA wires.

Shape memory alloys have one particular disadvantage for the use in tactile feedback devices. While transformation to Austenite usually happens quite fast, returning to Martensite is a slow process since it depends on cooling-down of the material. Thin wires of Nitinol can contract in less than 50ms but need time in the order of a second to relax. This delay can lead to misinformation since the state of the application differs from the state of the feedback device. A lot of ideas have been generated to overcome these problems. Since this is a cooling problem suggestions were made to use cooling liquids [WPFH98, MA03]. A US patent [HL92] describes a method of producing specially conditioned fast twitching fibers driven by electromagnetic pulses. Alternatively actuators can be forced mechanically to Martensite state, or SMAs having an intrinsic two-way effect speeding up the return path can be produced [ESC93]. These approaches have in common that they are often obtrusive and not very robust and some of them are not suitable for being used for a high number of shortening and relax cycles.

3 Design of the Tactile Feedback Actuators

From observing users during ergonomics studies for car interiors we had the impression that unobtrusive contact feedback at the fingertips would make the typical interactions with objects such as the steering wheel, flaps, openers, mirrors, and various knobs and buttons much more reliable. A mediating input device, such as a joystick with haptic feedback, is not an option for these types of interactions, since the user's hand needs to be used directly. Various versions of Sensable's Phantom device also used a thimble to provide haptic feedback directly at the fingertips. However, we wanted to use a more lightweight approach for the use in CAVE-like environments. Thus we decided to build only tactile feedback into thimbles for the fingertips. The idea was to use thin SMA wires wrapped around a thimble, which is open on the inner side

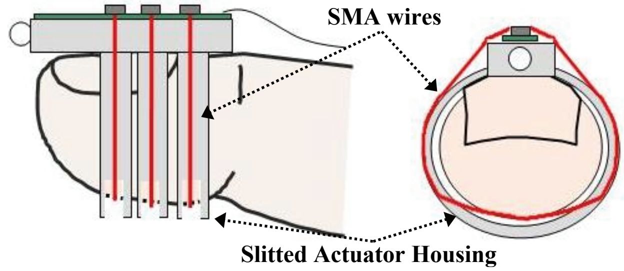

Figure 4: Schematic view of one thimble device

of the fingertips allowing the wires to be directly in contact with the skin (cf. figure 4). The wire contraction creates a localized sensation on the fingertip, which should be easy to perceive.

The thimbles were created in a selective laser sintering process using polyamide. Laser sintering is an additive process, which does not need any special stilts. Thus the manufacturing process does not need to be considered during the design phase. Both, the mechanical and thermal stability of the material are very high. In contrast the relatively low resolution of 1mm and the roughness of the surface are disadvantageous, but for prototypes acceptable. We developed four prototypes with incrementally improved designs (cf. figure 5). We started with a single thimble housing one SMA wire. This design step was used for proof of concept, showing if the user is able to feel the contraction of the wire. For the second design we increased the number of actuators per thimble device. As we used a clamped connection with M2 screws for the wires, the maximum number of actuators mainly depended on the size of the screw heads. The head diameter was 3.8mm, so we decided for a spacing of 6mm between the wires. Four actuators can be attached to the thimble device this way. However for the following two prototypes we reduced the number of actuators to three for the index and middle finger and two for the thumb because of space constraints and design limitations. In particular our device control board (cf. section 4) was able to control only eight

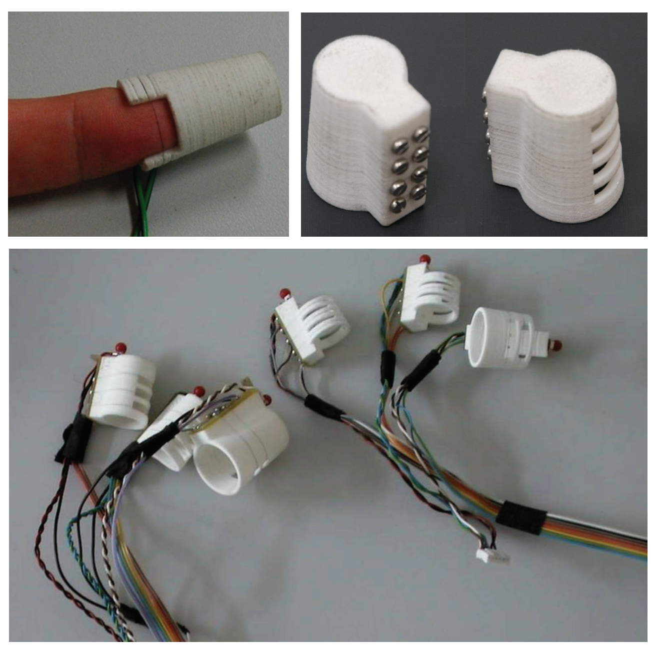

Figure 5: From concept to prototype: 1st study with one SMA-actuator (upper left), tests with several actuators per thimble (upper right), 3-finger approach connected to finger tracking system (lower left) and final prototype (lower right)

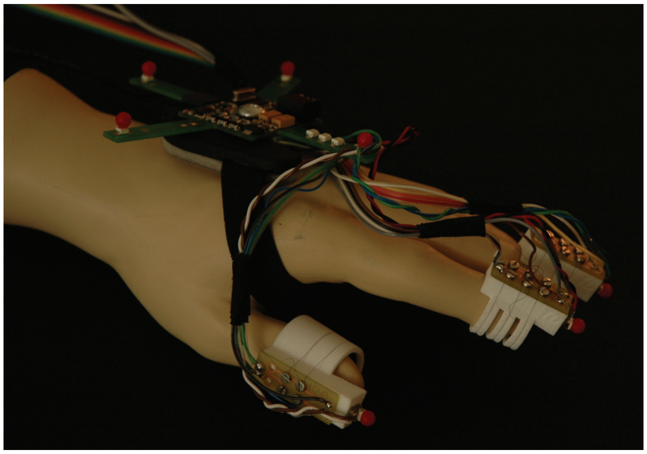

Figure 6: Final prototype of our tactile feedback system combined with the finger tracking system by A.R.T.

wires simultaneously. The third and the final prototype were combined with an optical finger tracking prototype developed by A.R.T. GmbH [@ART]. First evaluations in an immersive environment were performed with the third prototype leading to the final version with improved ventilation for the finger tips. We removed as much as possible extraneous thimble material without reducing the robustness of the finger actuator.

A critical parameter is the fit of the thimbles on the users' finger tips. There is an ISO standard describing hand parameters – ISO 33402. However some more parameters than specified are needed for building thimbles, in particular the outer phalanges' lengths and circumferences are not defined by this standard. We chose the dimensions of the thimbles by simply averaging the hand parameters of eleven subjects. For the middle and index finger we used an inner diameter of 17mm narrowing to 11mm and a length of 28mm. The thumb device has an inner diameter of 23mm narrowing to 18mm and its length is 35mm. These thimble sizes fit most of our users. However people with either rather big or quite small fingers would require the development of adjustable thimbles or thimbles of different sizes would have to be provided.

Another challenge is the connection of the SMA wires to the power supply, which is commonly done by a proprietary soldering process. Improper soldering can result in losing the memory effect. Instead we chose to clamp the wires with screws on the back of the thimble (cf. figure 6).

As mentioned before only small length changes can be realized if a long lifetime of the actuators is important. One of our first tests aimed at the recognizability of these small wire contractions. We found that a 50mm long wire wrapped around the first thimble prototype shortens about 1.5-2.5mm by applying a current. Users were able to notice the effect without problems even though this creates only a very small impression on the skin

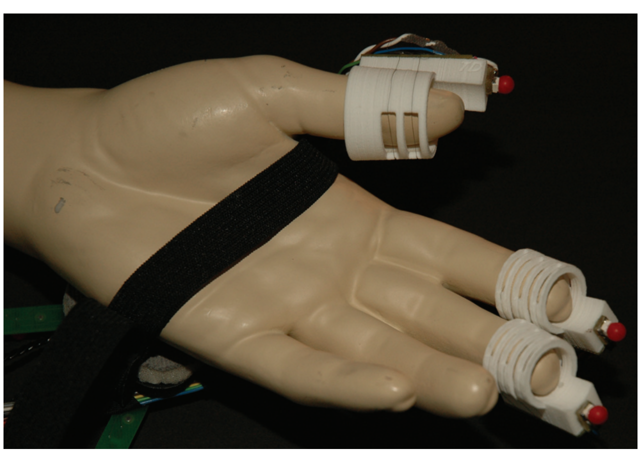

Figure 7: The inner side of our final prototype.

We performed some experiments with individually controlling the three SMA wires of a single thimble and discovered that the impressions of the different wires can be distinguished very well. Users can even feel patterns displayed by activating the actuators sequentially. Due to the design and control of our prototype the number of actuators is limited. A more elaborate fastening mechanism and a more advanced controller design would allow us to add more actuators to each thimble. As mentioned in section 2.2 the two-point threshold of the fingertips is around 2.5mm. So actuator arrays with interspaces larger than this discrimination limit will generate discretely perceivable signals.

Our objective was to augment finger collisions with our tactile feedback at the finger tips. Thus tracking of individual fingers was required. We integrated a prototype of an optical finger tracking system developed by A.R.T. GmbH. This system consists of a hand target with four active markers and one active marker for each finger. The finger markers are usually attached to plastics thimbles. We glued them to our thimbles as shown in figure 6 and 7. Currently only three tracked fingers per hand are supported.

Our incremental design process led to a prototype consisting of a small backbone for holding the screws and thin rims around the finger (cf. figure 6, 7). There are three actuators for the middle and index finger and two actuators for the thumb. This final design showed a good compromise between stability and wearing comfort. The thimbles are lightweight and easy to put on. Ring finger and pinky are not yet supported, but they are less relevant for most of our interactions.

4 Device Control

We conducted experiments with a set of different alloy types and diameters to select the appropriate wires and identify the control parameters for the electrical design. To achieve a rapid transformation the actuators have to be as thin as possible, of course limited by the tensile strength of the material. Tests showed that 80µm wires have enough tensile strength for our purposes and showed the best dynamic performance.

The shape memory alloy is directly heated by electrical current using a pulse width modulation (PWM) signal to initiate the shortening process. We utilized the skin as a heat sink for the

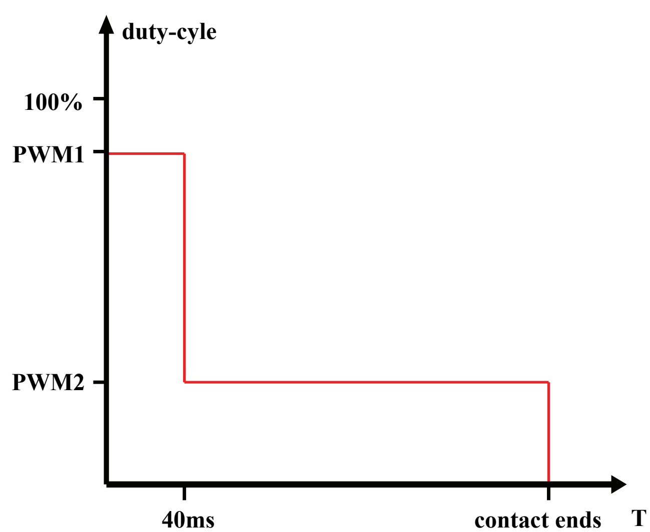

Figure 8: High duty-cycles display contact events, low duty-cycles ongoing collision.

wires since there is no risk for the users to contract burns if the actuators are thin enough and the transformation temperature is reached within a short time – for the 80µm wire in less than 50ms.

We used a pre-trained SMA type M from Memory-Metalle GmbH, Germany. It had a diameter of 80µm and a length of approximately 50mm per actuator. This material has a T_{AF} of around 65°C. From studying the sensory system, we knew that an ongoing impression of the fingers' skin – reporting an ongoing collision for example – can only be recognized by one of the responsible sensor cell types. The impression generated by our actuators is a stimulus which is not strong enough to be perceived continuously. Our tests revealed that applying a low duty-cycle of the PWM signal results in a perceivable vibration of the material. This is used to provide a second tactile pattern. The material is transformed and contracted using a high duty-cycle for a short period of time. Afterwards a low duty-cycle is applied producing an ongoing stimulus (cf. figure 8). During the low duty-cycle the wires already cool down and relax, which remains unnoticed by the users. Stopping the low duty-cycle and thus the vibration at the end of a collision with a virtual object is immediately recognized. This way the slow response time for the relaxing process of the SMA wire is obscured by the vibration signal.

Another important fact to consider is power consumption. The power transferred by a PWM signal is calculated in the following way (cf. equation 1). We chose to time multiplex the wires, so the maximum duty-cycle per actuator is one divided by the number of actuators – eight wires in our case.

Experiments revealed that the 80 µm wires with a resistance of 11Ω can be excited within 40 ms running at 5V and using an 80% duty-cycle. This results in power requirements of 1.81W following equation 1. A voltage of at least 12.6V has to be applied for achieving the same power while multiplexing with only 1/8th maximum duty-cycle (cf. equation 2). The control board was designed to power the eight wires with 13.8V.

$$P = \frac{U_{on}^2}{R} \cdot \frac{t_{on}}{t_{on} + t_{off}} + \frac{U_{off}^2}{R} \cdot \frac{t_{off}}{t_{on} + t_{off}}$$

$$if \ \ U_{off} \ \ is \ \ 0$$

$$P = \frac{U_{on}^2}{R} \cdot \frac{t_{on}}{t_{on} + t_{off}}$$

Equation 1: Power transferred by a PWM signal

$$U_{new} = \sqrt{1.81W \cdot 11\Omega \cdot 8}$$

$$U_{new} = 12.6V$$

Equation 2: Voltage to be applied due to multiplexing

We developed a microcontroller based circuit board for communication with the VR application, which allows us to drive the time-multiplexed wires with a PWM signal. We used an ATMega8 microcontroller running at 8 MHz. The ATMega8 from Atmel Corp. is a RISC processor with 8kByte flash program memory, 1kByte SRAM, 512 byte EEPROM, 6 or 8 channel 10 bit A/D-converters, providing 8 MIPS at 8MHz. It is programmable using the assembler instruction set or the GCC tool chain. We developed the firmware in C using the avr-libc version 1.4.4.

The micro-controller generates 3 signals:

- a PWM signal for each actuator channel
- a signal to switch the channels
- a reset signal for the channel counter on the printed circuit board (PCB)

To switch between the eight channels, a 4017 decade counter is used. The switching clock for this circuit is provided by a timer 0 overflow interrupt of the microcontroller. After eight switching cycles a reset signal is sent. A separate PWM duty-cycle is applied during the time-slot for each channel.

It is possible to extend the board design to control more wires – e.g. to support 15 wires, 3 for each finger tip – but the voltage level has to be adapted as we have shown above. Alternatively a micro controller with more PWM channels could be used.

5 VR System Integration

We integrated our tactile feedback device into the VR system VD2 developed by VRCom GmbH. VD2 consists of three main components (cf. figure 9):

- the interaction manager
- the device manager
- the Y rendering kernel

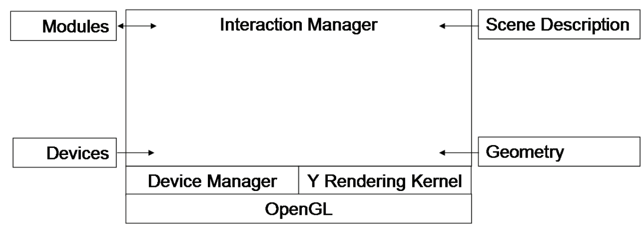

Figure 9: VD2 architecture

The *interaction manager* keeps track of all actions in the virtual environment such as the users' input. It is configured by a script which defines the static and dynamic properties of the scene. The description is based on the following primitives: *events*, *actions,* and *objects*. Certain events evoke predefined actions, for example, a collision (event) of two geometries (objects) cause a tactile feedback (action).

Initialization and control of input devices is handled by the *device manager*. A tactile feedback device should be realized as an IDEAL device in the *device manager* of VD2. Unfortunately, the *device manger* supports only input devices. So the device driver for the tactile feedback had to be realized as an extension to the *interaction manager*.

The rendering kernel Y is based on OpenGL. It is responsible for loading the geometries, building a hierarchical tree, and rendering the scene.

We implemented the driver code for our tactile device in a dynamically shared object (DSO). VD2 allows several function types for DSOs:

- *init* functions, executed once during start of VD2
- *callback* functions, executed on previously defined events
- *loop* functions, called each frame
- *exit* functions, called at VD2 termination

The init function is used to open the serial port for communication with the micro-controller. The callback function is called each time a collision of the fingers with virtual objects is detected by the application. Depending on which finger collides, a two byte command sequence is sent to the micro controller. The first byte contains the command itself:

- contact start
- contact end
- set contact-start PWM duty-cycle
- set contact-hold PWM duty-cycle
- set contact-start duration

The second byte supplies the following values, if required:

- information on which wire has to start or stop

- values for PWM duty-cycle and duration

Since these values are 8bit wide, a maximum of 255 wires can be addressed, and the PWM duty-cycle is also adjustable in the range of 0 and 255.

6 PILOT STUDY

We evaluated our tactile feedback system in a first pilot study to get an impression of the usability of the thimbles, the acceptance of this type of feedback by the users, and the influence on interaction performance. For this study we used the final thimble prototype as shown in figure 6 and 7 including the finger tracking. Our Immersive Interactive Data Model (I²D), a module of the VR system VD2 [MF05] enables users to manipulate parts of a virtual car interior in immersive environments using a pseudo-physical approach (cf. figure 10). This application can be used to investigate ergonomic questions – like reachability or visibility – before first hardware prototypes are built.

Figure 10: Typical situation of the CAVE application

The manipulation of virtual car components using the corresponding real-world gestures promises to reduce the learning effort. However, this type of direct interaction creates depth perception problems due to the shift of focus between the users' hands and the projection screen and the conflicting focus and convergence cues. It is often difficult to judge the hands' and fingers' exact position relative to a displayed object on a purely visual basis. Our hypothesis is that our tactile feedback system increases the reliability of direct interaction tasks due to the perceptibility of hand-object collisions.

Eight subjects participated in the study. The users – partly novices to immersive VR applications – were asked to perform common interactions with a car interior. Feedback to the fingers was given while a collision of a particular finger and a virtual object occurred. The following interaction had to be performed with and without our tactile feedback device:

- Open the drivers' door
- Pull down the sun visor
- Turn the steering wheel
- Open the glove compartment
- Operate the rotary light switch
- Adjust the interior mirror

Task completion times were not measured, since the application is too complex to achieve reasonable results in such a pilot study, but each participant was observed and notes were taken. After the tasks had been performed the subjects were asked to fill out a questionnaire. The following three questions yielded the most interesting results:

A) intensity of the feedback
B) quality of the feedback, i.e. how well does this kind of feedback match the actual application
C) the improvement due to the tactile feedback compared to the system without tactile feedback

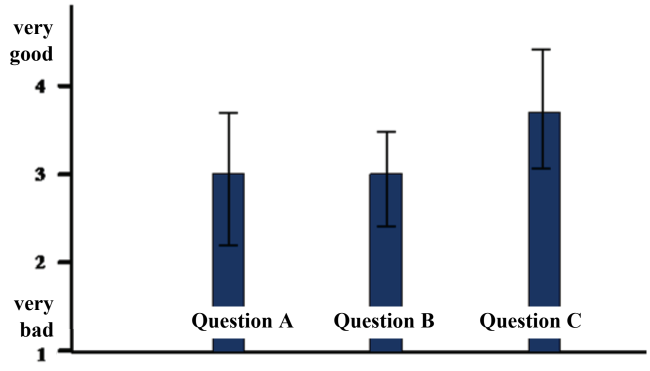

Figure 11: Results of the questionnaire

The users were asked to rate each question on a one to four scale, one corresponding to very bad and four to very good. The results for these three questions (cf. figure 11) show that our approach to tactile feedback was well received. Users clearly preferred the tactile feedback system over the system without feedback. The intensity of the feedback seems to be strong enough and the quality is also judged as good.

Users pointed out that the way the feedback was provided – by an impression at the finger tips – matches well the grasping actions of the application. This sensation is quite similar to what is felt when touching objects. We observed that in particular small objects that are almost completely occluded by the real hand, like the rotary light switch, can be operated with much more reliability when using our tactile feedback system. This was also explicitly mentioned by some of the participants. Users did not complain about delays in the system, even though we measured the wire contraction to be around 50ms and estimated the time from the VR system to the microcontroller to be between 30 and 60ms.

Users had a wide range of hand and finger sizes. Difficulties in mounting the thimbles correctly to their fingers revealed the necessity of adjustable thimbles or at least the availability of a variety of thimble sizes. The amount of feedback felt by the user directly depends on the correct fit of the actuators. As we expected from our studies on the haptic sensory system (cf. chapter 2.3), users were not able to perceive an ongoing impression of the shortened SMA wires. Instead the vibration effect described in chapter 4 was used to communicate an ongoing contact with a virtual object. Most users could clearly tell when the contact with a virtual object occurred and when it ended. However some subject could not feel the vibration effect. Further investigation into this problem revealed that a good fit of the thimble is necessary to feel the vibration of the SMA wire. Additionally we found that the parameters of the electrical signal for creating the vibration, in particular the PWM frequency, seem to be slightly different for some users.

Participants of the study and further people experimenting with the system did not complain about the pressure of the very thin wires – 80µm – if the thimbles matched the finger sizes. In addition heating the wires for less than 50ms to initiate the shortening process was not mentioned as a problem, as the temperature change was hardly felt at all.

7 Summary and Future Work

We have designed a new tactile feedback system for immersive VR applications. The system consists of a tracked thimble for each finger – currently restricted to index, middle and thumb – with shape memory alloy wires looped around each thimble. The shortening and relaxing of the wires is controlled by a microcontroller, which receives commands from the virtual reality application. We use the tactile feedback for communicating finger contacts with virtual objects to the user. The particular problem of the SMA wires – the slow relaxation process – was resolved by complementing the pressure on the finger surface through shortening of the wire by a vibration of the wire using a pulse width modulated signal. Our pilot study revealed that users clearly preferred the tactile feedback over a system without feedback and felt much more in control of manipulation tasks in the car interior, such as turning the steering wheel, pulling down the sun visor and others.

Our proof-of-concept prototype was well received by our users and during the pilot study, but these results need to be confirmed by an extensive user study. Of course, there is still much more work on the way to a reliable and robust device for commercial purposes. Three main issues have to be considered in a next design step:

- Different size thimbles or adjustable thimbles need to be provided.
- A wireless solution would be beneficial, since the hand and finger tracking system is already wireless. Therefore, a solution for powering the device based on the calculations in equation 2 and radio control of the device have to be developed. Ideally this should be integrated with the hand tracking system to avoid doubling these components.
- Further increasing the response behavior could be reached by incorporating approaches that raise the frequency of SMA material transformation as presented in chapter 2. However, our approach with already low response times complemented by the vibration of the wires seems to communicate the moment of contact – indicated by the fast contraction of the actuators – quite well, whereas stopping the vibration helps to realize the end of the contact. However fast finger tapping can not be simulated by our approach, which is hardly necessary for our studies, but might be relevant for other scenarios such as simulating the operation of a touch screen.

In our current version we attached two actuators to the thumb thimble and three actuators to the index and middle finger thimble. This configuration allows us to display tactile patterns, which we confirmed through first experiments. These patterns can be recognized since our approach does not only rely on vibro-tactile stimuli. The question is how many actuators and which patterns can be differentiated? One idea for making use of the multiple actuators is the improvement of the positional and temporal precision of the contact feedback. Adding further feedback units for other finger phalanges could even further enhance the localization of the feedback. However care must be taken to design an unobtrusive solution.

The combination of the precise finger tracking system with our tactile feedback approach has shown the potential to significantly facilitate direct finger-based interaction with virtual objects. The availability of such intuitive and convincing interaction techniques provides good arguments for the further substitution of hardware prototypes by virtual mockups in the development process of the automotive industry.

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