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Usability of a virtual reality system based on a wearable haptic interface

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Abstract— **Recent scientific works regarding interaction in virtual realities presented many different approaches for haptic feedback. However, the usability of a wearable device, which deflects forces on the user's body in some way, has not been evaluated up until now in the context of virtual realities. In this work we present the application of a wearable haptic interface in virtual realities and evaluate its usability. The wearable haptic interface can be carried like a backpack, is embedded in a multimodal virtual reality framework and enables its user to touch and manipulate virtual objects with his right arm. We evaluate whether the deflection of forces on the user's torso degrades the sense of presence and assess the usability and user acceptance of the wearable haptic interface in a virtual reality scenario. We conducted a presence questionnaire with 18 test persons in order to acquire subjective measures. As an objective measure a task performance experiment was carried out.**

I. INTRODUCTION

The demand for an intuitive way to interact with computer generated environments increased in the last decades. The effectiveness of a virtual reality system is measured by its usability, which is governed by the grade of immersion and by the intuitiveness of the users orientation, navigation and interaction. A virtual reality interface that incorporates a high usability should not confine the user in his tasks. One of the most important characteristics of such an interface is the accessible workspace. A large workspace allows the user to behave in a natural way. This minimizes the adaptation time and increases the intuitiveness significantly. However, most haptic interfaces provide a small workspace, therefore the control of the avatar and interactions in the environment must be based on an interface that the user has to adapt to in prior. A small workspace is the result of optimizing the device's stiffness in a trade-off for available workspace and the device's weight. A high stiffness is important for some specific type of tasks e.g. high precision assembly or investigation of an object's stiffness in a virtual environment. But for a wide class of tasks a high stiffness is not necessarily required.

In our research work we have been striving after a lightweight haptic interface system, which can be carried on the user's body. It allows the user to move in and access large workspaces in a natural manner. As a prototype we developed a wearable arm exoskeleton - see Fig. 2. The design of the mechatronics and an evaluation of its mechanical properties are presented in [8]. The device is characterized by a low weight but also by a limited stiffness.

Consequently the question arises whether a wearable haptic interface (WHI) does provide a high degree of usability in virtual reality applications. In this paper we present the surprising - at least for us - results, which motivate us to see lightweight wearable exoskeletons as the best choice for haptic interaction within large workspaces. The two main questions we had to answer were: can we compensate the limited stiffness of the device with other modalities (like vision and audio) and will forces that get deflected on the user's torso during interaction disturb the user while performing tasks in the virtual environment. In this paper we investigate whether too much emphasis has been given to properties like the stiffness of a WHI and propose an index of the usability of our system by extending a presence questionnaire with a task performance assessment with eighteen test persons - see Sec. IV. The experiments were conducted in two different interaction scenarios. In the first scenario a task had to be completed using our wearable haptic interface and a virtual reality framework. Navigation and haptic interaction in the second scenario was based on a 3D-mouse and a desktop haptic interface. From the results of these experiments we conclude whether a high grade of fidelity and immersion can be achieved with the WHI when it is used in virtual reality scenarios. We interpret the results of the experiments in Sec. V and analyze whether our system provides a high degree of usability and immersion despite the mechanical limitations of the wearable haptic interface in Sec. VI.

II. RELATED WORKS

Nowadays there is a broad range of interfaces for virtual reality applications available. Interfaces for visual presentation of a virtual environment range from computer screens sometimes in combination with shutter glasses for 3D-display to stereoscopic head-mounted displays (HMD) [1] and projection based displays like 3D-workbenches and CAVEs [2].

Haptic feedback can be realized in different ways and the two main classes for haptic feedback devices are stationary and mobile designs. Stationary devices have a limited workspace therefore the user has to rely on another input device like a 3D-mouse in order to navigate in a large virtual environment. Examples for desktop haptic interfaces are the Sensable PHANTOM (http://www.sensable.com), the Novint Falcon (http://home.novint.com) and the Force Dimension DELTA (http://www.forcedimension.com).

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Mobile haptic feedback can be realized in different ways. One approach employs a robotic arm for haptic feedback, which is fixed on a mobile platform. The position and orientation of the user gets tracked and the platform moves in order to maximize the reachable haptic workspace and minimize unwanted forces. The group of Prof. M. Buss have presented sophisticated results with this approach and evaluated an interface for telepresence based on this research [3]. A state of the art grounded haptic device - as for example the PHANTOM - mounted on a mobile platform has been evaluated in [4]–[6].

Another methodology makes use of a robotic arm for haptic feedback, which can be carried by the user and deflects forces during interactions on the user's body. Devices similar as presented in [7]–[10] in combination with a tracking solution enable its user to exploit an arbitrarily large workspace and navigate in an intuitive manner. However, an evaluation of the usability and fidelity of wearable haptic interfaces is still pending. Moreover, most solutions are limited by the degrees of freedom in which forces can be exerted. Therefore the evaluation of the usability of a wearable haptic interface is important in order to assess which effects can be simulated in a realistic manner. The WHI, which is evaluated in this paper, can exert forces in three degrees of freedom and therefore renders arbitrary haptic effects possible.

The degree of immersion of the different interface technologies differs as does the applicability in certain situations. An overview of the established technologies and systems can be found in [11], [12]. The assessment of a virtual reality system can be ambiguous, as the degree of usability depends not only on its technical specification but also on subjective impressions of its users. In the literature exist several different approaches for a subjective measure of the sense of presence in a virtual reality system like a 10-point rating scale [13]. In order to have a presence measure with a high reliability we performed a presence questionnaire as proposed by Witmer et al. [14].

III. VIRTUAL REALITY SYSTEM

One goal of our research is to investigate which effects can be properly presented with a wearable haptic interface in virtual realities. After designing and evaluating the mechatronics of the wearable haptic interface we developed a virtual reality framework for its application. The key contributions of our work are the integration of a simulation engine for physics both in the visual and the haptic renderer, extending a haptic renderer by optimal topologies for the extraction of geometries in large complex virtual scenarios and the design and integration of a 3D audio synthesis module. The framework consists of three main building blocks that calculate the reactions of the system to the users' actions by means of visual, auditory and haptic feedback. In order to provide access to an arbitrarily large workspace modifications compared to existing solutions had to be made. The result is a virtual reality framework, which enables the user to interact with the whole right arm while force feedback is presented to his or her hand. The user of the system is able to access the arbitrarily large workspace and can move freely in the virtual reality. In the following sections and in Fig. 1 we are giving an overview of how the components of the framework are realized.

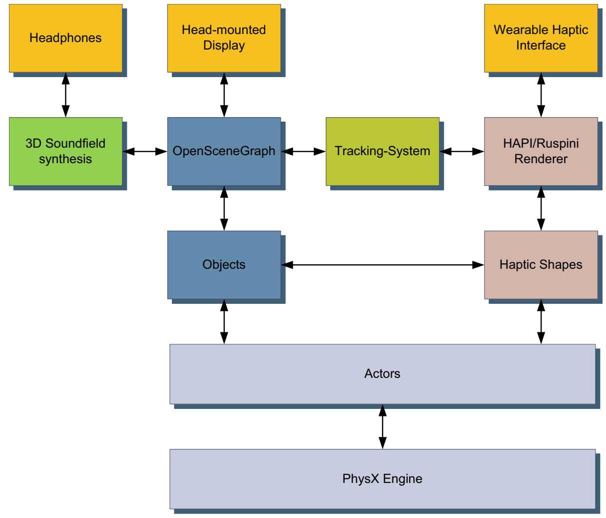

Fig. 1. Virtual reality framework components and data exchange

TABLE I
SPECIFICATION OF WORLDVIZ PPT4 OPTICAL TRACKING SYSTEM

Relative Precision	$<$ 1 millimeter over $3*3*3$ m volume
Absolute Accuracy	$<$ 0.5 centimeter over $3*3*3$ m volume
Update rate	60 Hz
Minimum latency	18 milliseconds
Maximum latency	20 milliseconds

A. 3D VISUAL RENDERING

For the display of the 3D-scene we decided to rely on a head-mounted display. We want to enable the user of the virtual reality system to make use of haptic feedback presented by a wearable haptic device. An occlusion by the user's arm and the haptic device in the view disturbs the stereoscopic impression in projection based systems like a 3D-workbench or CAVE. Therefore we cope with the fact that a head-mounted display provides a limited field of view. Nevertheless, it enables its user to concentrate on the three-dimensional graphics without getting distracted by his real surroundings. For an optimal scaling of the field of view we had to match the visual representation of the HMD to the actual scale of objects in the haptic modality. We use an optical tracking-system in combination with inertial measurement units (IMU) in order to track the user's body and head. The technical specifications for the tracking systems are listed in tables I and II. Rendering of the visual 3D-scene is realized with OpenSceneGraph (OSG) (http://www.openscenegraph.org), which is a scenegraph system built on top of OpenGL. Its wide functionality enables us to keep track of object-object dependencies and hierarchies.

TABLE II

SPECIFICATION OF THE INTERSENSE INERTIACUBE3

RMS Accuracy	1° in yaw, 0.25° in pitch and roll at 25° C
RMS Angular Resolution	0.03°
Minimum Latency	2 milliseconds
Maximum Angular rate	1200° per second

Fig. 2. A person using the virtual reality system and interacting with virtual objects

Stereoscopic display of the rendered scene is realized with the NVisor SX by Nvis (http://www.nvis.com). We combined the comprehensive functionality of OSG with the physical simulation engine NVidia PhysX (http://www.nvidia.com) in order to animate rigid body physical dynamics and simulate physical effects during interactions.

B. HAPTIC RENDERING AND INTERACTION

Over the course of the last two years, our laboratory developed a novel prototype haptic feedback device that can be worn by the user in combination with a head-mounted display and headphones - see Fig. 2. The device has a weight of 13.5 Kg and a peak force output of 40 N. It provides the user with haptic feedback on the right arm - see [8] for details of the design and properties of the mechatronics and an evaluation of the mechanical performance. The user is wearing the WHI like a backpack and can move around intuitively while carrying the device. The user is able to wear the device, therefore it is classified as a non-grounded design and deflects forces on the torso and back during haptic interaction.

As a software backend for haptic rendering we use HAPI (http://www.h3dapi.org/) and rely on the algorithm for constraint-based rendering as presented by Ruspini et al. [17]. We modified the haptic framework in order to apply it in large scale virtual environments. As a large virtual scenery can be geometrically complex, we utilize an octree for the extraction of the relevant geometry depending on the position of the haptic proxy and shapes in the virtual reality. We modified the traversal of the octree so that a lookup of the relevant polygons for haptic rendering is based on information about the neighboring leafs in the tree that contain geometry. The haptic proxy can not jump from one time step to the next. Therefore it is feasible to exploit that geometry has to lie within a certain distance of the haptic proxy. This accelerates the tree traversal and also ensures us that the constraints used for haptic rendering are generated fast enough. Unstable behavior like "falling-through" of the proxy or oscillatory behavior due to a fast change in the constraint planes is avoided. Haptic rendering is realized with a refresh-rate of 1000 Hz like recommended in other works [11], [12].

We want to enable the user to interact with objects according to laws of physics. Engines for simulating objects with physical dynamics are usually designed for the usage in the context of visual rendering. Therefore there was a need to find a reasonable way to couple a haptic renderer with the physical simulation. We investigated different techniques for virtual coupling and designed an interface between the haptics renderer and the physics engine. Virtual coupling is realized with a spring-damper-model. Position and velocity of the PhysX actor in the spring-damper-model have to be interpolated as the update-rate of PhysX is 60 Hz and therefore slower than the haptic renderer. After some research we realized that a critically damped spring-damper in dependency of the PhysX actor's mass gives the most natural and stable impression of objects with weight and physical dynamics. The mass of objects in the physics engine is well defined. Therefore we can critically dampen the spring-damper coupling by defining an arbitrary stiffness constant k for the spring.

C. 3D SPATIAL AUDIO SYNTHESIS

The third building block of the virtual reality framework synthesizes binaural audio queues and employs an auralization of a simple geometrical model of the virtual room or environment like shown in the schematics in Fig. 3. The audio synthesis module for virtual realities with a large workspace can simulate sound-sources on contact of the tooltip center point (TCP) with a virtual object, friction events, object-object collisions or sound-emitters, which can be placed arbitrarily in the virtual environment. The reverberation of the room model is realized by applying the mirror-image-method as presented by Allen et al. [16]. For binaural synthesis we use the head-related transfer functions as contained in the CIPIC database [15]. Sound-sources and the listener can move freely in the virtual environment, therefore we switch the head-related transfer functions depending on the angle of inclination of the sound.

The resulting output signals get fed into a mixing and compressing stage in order to avoid clipping of the signal in the output channel. Clipping would lead to audible distortions in the audio playback that disturb the spatial impression. The user is wearing headphones in combination with the head-mounted display. The orientation and position of the head

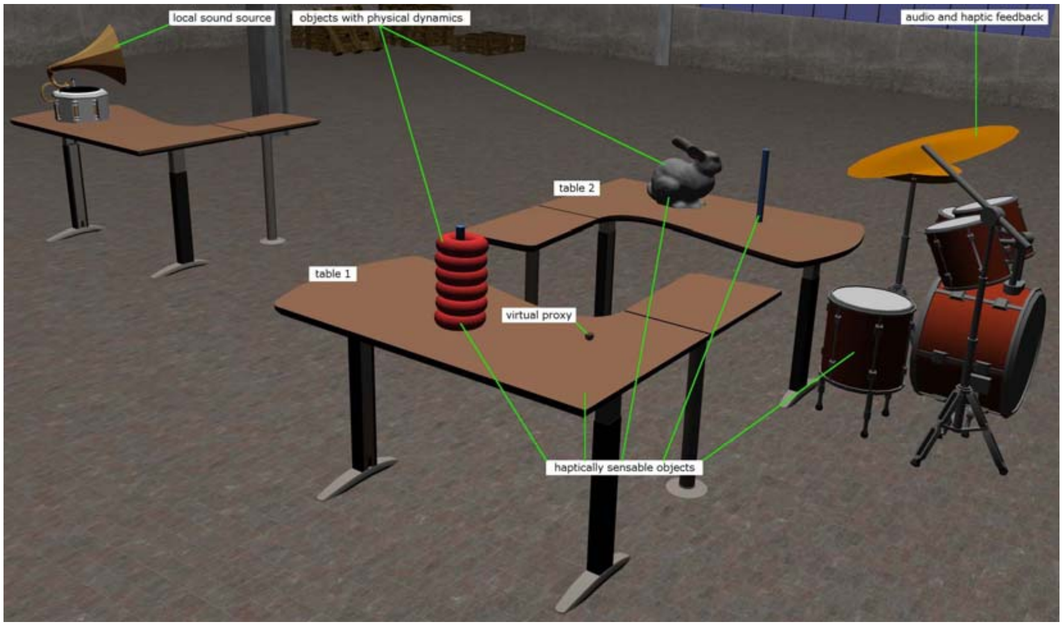

Fig. 4. Screenshot of the virtual reality scene used for the experiments

are determined by the tracking system.

IV. EXPERIMENTAL SETUP

For the evaluation of the usability and user-acceptance of the virtual reality system, we conducted a questionnaire and task-performance experiment with two different setups. 18 voluntary test persons participated in the survey. The test persons consisted of staff, students, scientific members of the laboratory and persons with no affiliation to the faculty. Except for two participants the test persons had little or no experience in using a virtual reality interface with haptic feedback. The virtual reality scenario as shown in Fig. 4 was made up of a factory hall in which we set up a combination of objects for the users to interact and play with. A virtual sound source playing back music was placed at the position of the gramophone. The Stanford Bunny and the toroids are objects with physical dynamics that can be moved, touched, thrown and carried around. The mass of the objects was set to 0.4 kg and the stiffness of surfaces in the virtual environment defined as 400 N/m with a damping of 40 Nm/sec. The user was able to grab an object by pressing and holding the trigger button of the joystick handle of the WHI. The rest of the objects were static but could be touched using the haptic interface. The test persons were also able to play the drum set, which gave audio and haptic feedback.

In the first experimental setup the test persons relied on the WHI, the stereoscopic head-mounted display and binaural audio synthesis presented with headphones. The second setup consisted of a Novint Falcon for haptic feedback in combination with a Spacenavigator by 3D-connexion (http://www.3dconnexion.com) and headphones. In this case the view of the virtual room was confined to one perspective and the users were able to translate the workspace of the Falcon haptic device with the Spacenavigator. Prior to each experiment the users were shortly instructed how to operate the haptic interfaces and which possibilities they had to interact with the virtual environment. In the beginning of each experiment the participants were given 5 minutes of time to get used to the experience by exploring the virtual environment and playing with the provided objects. Afterwards the participants were given the task to carry three toroids from the table nr. 1 to table nr. 2 and thread them over the empty cylinder one by one, as shown in the attached video. The test persons were told to complete the task as good and fast as they were able to. We measured the time it took each person to finish the task in both experimental setups. After each experiment a test person was asked to answer the 32 subjective questions of the presence questionnaire as proposed by Witmer and Singer [14]. The rating scale used was 1 to 7. A rating of 1 point was considered “low” or “do not agree”, whereas a rating of 7 points was considered “high” or “strongly agree”.

V. RESULTS

After finishing the experiments we grouped the users' ratings into two scales as proposed by Witmer and Singer [14]. The first scale consists of the major factors governing the degree of subjective immersion as perceived by the users. The major factors are subdivided into four items: Control factors, sensory factors, distraction factors and realism factors. The results can be interpreted as the subjective impression the user had of the virtual reality compared to his or her natural perception of interaction in reality. The sub-scale groups the evaluations of the test persons by the degree of realism in the sensory modalities and the degree of the quality of interaction. This includes: Subjective involvement and control, degree of naturalness of the immersion, the quality of auditory, haptic and visual sensations and the overall interface quality as perceived by the test persons.

In Fig. 6 (WHI) we show the results of the major factor scale when the test persons used the WHI to interact with the virtual reality and were free to walk around while being tracked by the tracking system. Compared to the subjective ratings of the second experimental setup using the Falcon and the Spacenavigator , as shown in Fig. 5 (Falcon&Spacenavigator), all the major factors were rated to be more immersive. The distraction factor is almost half as strong in case (WHI) as in case (Falcon&Spacenavigator). Test persons actually reported that they forgot about wearing the backpack of the WHI once they were fully immersed in the the virtual environment.

In Fig. 7 we show the results of the sub-scale grouping of the test persons' ratings. In the case of the system based on the WHI the ratings of the different modalities, the degree of involvement and control and the naturalness of the perceived impressions were all subjectively rated to be highly immersive. Specially in the haptic modality the users reported a much higher fidelity of the feedback compared to sitting in front of the screen and using a much stiffer table-mounted haptic interface with a small workspace in conjunction with a 3D-mouse.

The result of the objective task performance time measurements is shown in Fig. 8. It took many users almost 2-3 times as long to complete the assigned task of carrying the toroids and threading them on the cylinder on table 2. Interestingly one test person owned a 3D-connexion Spacenavigator and was used to navigate through three dimensional environments with it. It took this test person 39.66 sec to complete the task with the combination of the Falcon and the Spacenavigator and 31.48 sec when using the WHI. We reason that for the average user the WHI is highly intuitive and therefore

Fig. 5. Experimental setup of the table-top setup using the Novint falcon as a haptic interface in combination with a 3D-connexion Spacenavigator in order to exploit a large workspace

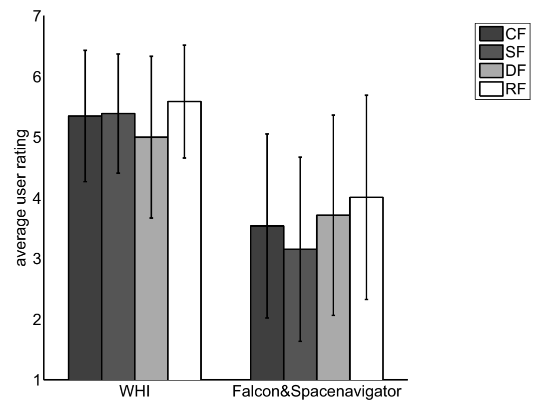

Fig. 6. Comparison of the subjective results of the presence questionnaire regarding our system based on our wearable haptic interface (WHI) and the system based on a combination of a Novint falcon for haptic feedback and a 3D-connexion Spacenavigator (Falcon&Spacenavigator) for movement of the workspace of the haptic device. The statistics of the major factors affecting the subjective sense of presence are shown. 18 test persons participated in the survey. Legend major factors: CF: Control Factors, SF: Sensory Factors, DF: Distraction Factors, RF: Realism Factors. In the case of the distraction factors (DF) a higher rating represents a lower degree of distraction

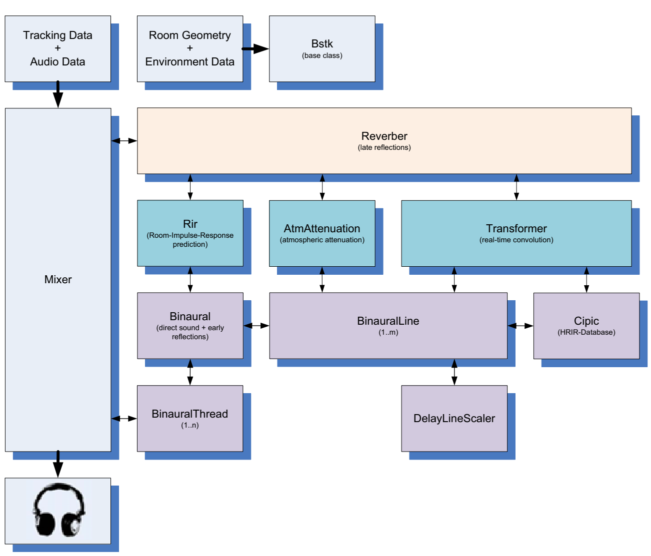

Fig. 3. Structure of the 3D sound-field synthesis module

enables unexperienced persons to get immersed in virtual reality without practice in prior.

VI. CONCLUSION AND FUTURE WORK

The main contributions of this paper are the evaluation of the usability of a wearable haptic interface in the context of virtual reality applications by conducting a presence questionnaire and a task performance assessment. We showed in which way existing virtual reality technology has to be modified and combined in order for the users to effectively use the system without prior adaptation. Concluding from the results of the presence questionnaire and the task performance experiment we reason that a virtual reality system based on a wearable haptic interface provides a high degree

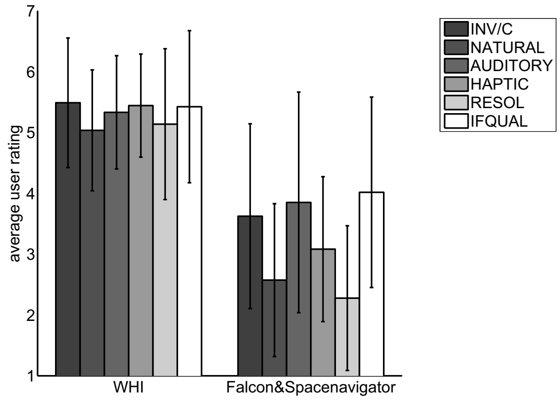

Fig. 7. Comparison of the subjective results of the presence questionnaire regarding our system based on our wearable haptic interface (WHI) and the system based on a combination of a Novint falcon for haptic feedback and a 3D-connexion Spacenavigator (Falcon&Spacenavigator) for movement of the workspace of the haptic device. The sub-scale statistics regarding modal performance and measures for involvement and control are shown. 18 test persons participated in the survey. Legend: INV/C: Involvement and Control, NATURAL: Natural impression, AUDITORY: Auditory impression, HAPTIC: Haptic impression, RESOL: Resolution in general, IFQUAL: Interface quality in general

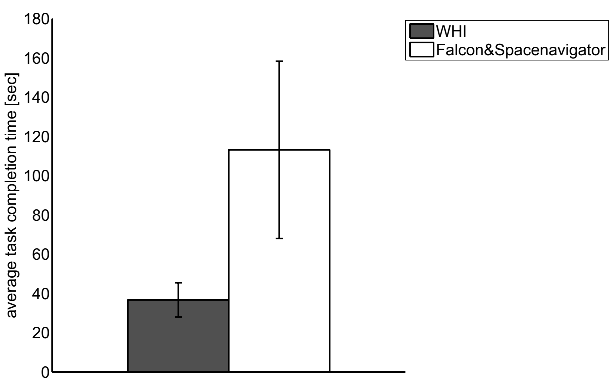

Fig. 8. Comparison of the results of the task performance experiment. The plot shows the average time it took 18 test persons to complete an assigned task in the virtual environment

of usability. We also draw as a conclusion that the mechanical properties of the device are feasible for an unconfined and transparent interaction with the virtual environment in most application scenarios. The fixture of the device via a backpack and the deflection of forces to the user's torso did not disturb the sense of presence. In fact, the users reported to actually forget that they were carrying the haptic device once they were immersed in the virtual environment. Our results show that the wearable haptic interface is an exciting starting point for the development of future human-computer interfaces. Future work should include the development of new prototypes that incorporate six degrees of freedom of force feedback. The device can also be extended by a second arm and research should be conducted about using a similar system in virtual cooperative scenarios. Other approaches for mobile haptic interfaces, which provide access to large workspaces in virtual realities, should be compared to the results of this work. Possible application scenarios are rapid prototyping, appliance in the rehabilitation of stroke and amputation (phantom pain) victims, art, entertainment and training simulations to name a few.

VII. ACKNOWLEDGMENTS

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