Efficient Bimodal Haptic Weight Actuation

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Abstract. In virtual environment scenarios the physical object property *weight* is rarely provided for operators due to its extensive technical complexity.

This paper addresses two approaches that both rely on pseudo-haptic feedback and that enable an efficient display of weight: *pneumatic* and *control/display* feedback. The former offers the substitution of proprioceptive weight perception by asserting well-defined pressure levels to the operator's wrist while the latter feedback mode encodes weight by visually altering the motion of the virtual hand compared to the real hand movement. Two experiments (A and B) were conducted in order to derive Stevens' functions that express the relationship between objective feedback settings and subjective weight perception. Additionally, a conjoint analysis (experiment C) was carried out that quantifies the weight of each single feedback modality in simultaneous feedback conditions. Finally, the results of user ratings regarding the quality of the bimodal feedback are presented.

Both displays prove to be of value as the majority of human test subjects report haptic perceptions without any real haptic stimulation.

Keywords: Pseudo haptic feedback, weight perception, haptic feedback, pressure sleeve, pneumatic feedback, control/display ratio, CDR, virtual reality, psychophysical scaling, conjoint analysis.

1 Introduction

In teleaction scenarios, a human operator usually controls a robot which is located at a remote environment. In order to do so efficiently, the operator needs feedback of his actions at this remote location, be it visual, auditory, haptic or any combination thereof. In the best case the operator would get exactly the same quality and quantity of feedback as he can perceive in everyday life [1].

Scientists and engineers are still working on getting as close as possible to this perfect teleaction system: haptic feedback quality catches up with already high quality visual and auditive systems; multi-degree of freedom actuators [2] or exoskeletal solutions [3] allow force feedback; surface roughness is simulated by miniature voice coils [4], vibrating dc-motors [5] or pin displays [6], to name just a few.

In this paper an alternative approach for simulating the weight of an object is presented: instead of relying on complex, heavy, and expensive hardware the potential of pseudo-haptic feedback and substitution is used. Pseudo-haptic feedback does not

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provide any *real* haptic cue but it makes use of the fact that human haptic perception is also influenced by appropriate visual and auditive stimuli (see section 2.1). The pneumatic device substitutes the cues normally gathered by arm and shoulder proprioception for pressure receptors located around the wrist (see section 2.2). In section 3 three experiments are presented that deal with the human perception of these new feedback modalities; in section 4 the results are discussed against the background of immersive virtual or telepresence scenarios.

2 Haptic Feedback Rendering

Both approaches of simulating weight feedback are described in detail below. Operators are equipped with a head mounted display[1] that is tracked by a Flock of Bird device[2]. Besides, a P5 data glove[3] is used, but only the finger bending is assessed. The tracking of the hand is provided by a second Flock of Bird sensor. The technical set-up is shown in figure 1.

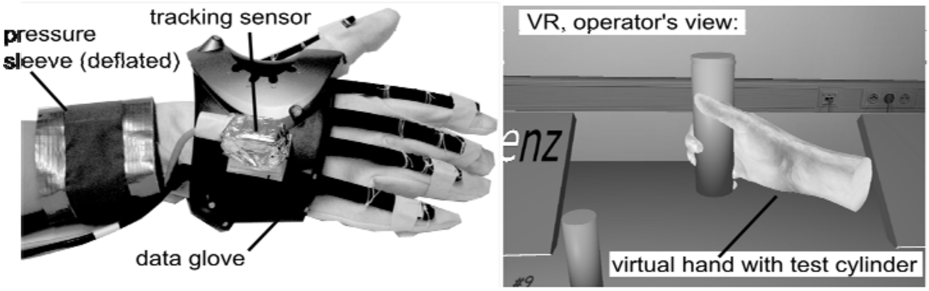

Fig. 1. Data glove (left) and virtual hand with a test cylinder (right)

2.1 Pseudo-Haptic Weight Feedback (Control/Display)

The idea behind pseudo haptic feedback is to make use of a human's ability of interpretation: although when lifted, a virtual object may not have any physical weight at all, it may feel heavy if the object's movements correspond to physical laws: Normally, a heavy item is lifted more slowly than a light one. So based on the acceleration or the speed of motions a human may form an implicit hypothesis on the weight of an object when it is picked up.

Biocca et al. [7] could demonstrate this cross-modal phenomenon (visual to haptic transfer) by implementing a snap-to-spring algorithm into a virtual environment and thus inducing a feeling of physical force without providing any real haptic actuation. Dominjon et al. [8] show that the visual cues that are given to subjects while weighing two virtual balls influence their discrimination ability. The faster the balls move the lighter they seem. Similar results of pseudo-haptic feedback can be found for the perception of roughness [9] and for the spatial interpretation of actually flat surfaces [10].

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[1] Cybermind Visette 45; 1280x1024 pixel, 60Hz.

[2] Ascension Technology Corp.; ERT set-up used.

[3] Essential Reality.

In general, the ratio between the movement of the real hand and its virtual visual display determines the strength of the effect. A "*control/display ratio*" (CDR) below one means that the object's movements are displayed faster than they are commanded (which again is perceived as lighter or smoother), whereas a ratio larger than one results in a decelerated behaviour (which is perceived as heavier or rougher). A CDR value of one is a neutral setting as both real and virtual movements match perfectly and no pseudo-haptic feedback is provided.

Within this work pseudo-haptic weight feedback is implemented by altering the hands' tracking data along the vertical z-axis: the Flock of Bird tracker feeds the data of the hand position into the VR program[4]. Here, the position data is downsampled to 60 Hz and the virtual hand is moved with this rate, too. Once an object is lifted the position data stream is expanded by interpolating further vertical position data in between already existing data; the position on the horizontal plane is not altered and it is displayed as tracked. The higher the simulated weight is, the more additional z-positions are inserted. As the position data is still processed with a constant 60 Hz, a FIFO (First-in-First-out) memory is filled and it can only be reduced again if the operator stops lifting the virtual object (a small deadband is provided) or if it is released. So the operator perceives the z-reactions of the virtual hand as decelerated compared to the commanded movements and thus, it is assumed to induce an impression of pseudo-weight.

2.2 Pneumatic Weight Feedback

The substitution of force or torque feedback by visual stimuli (e.g. force arrows) has been used successfully in minimally invasive surgery scenarios [11]: instead of stimulating operators haptically, they receive force or tactile feedback that is encoded visually. Just the same, auditive substitution has been proven to be beneficial for some micro assembly tasks [12]. Especially, when enhancing haptic actuators or when auditive and visual cues are combined a positive effect of sensory substitution can be expected.

In this domain a novel concept is the sensory substitution of proprioceptive weight perception by applying pressure around an operator's wrist. In this part of the hand, the proprioceptors cannot be stimulated without relying on "bulky" actuators [2][3]; however, it is easier to stimulate the epidermal Merkel cells [13] by applying pressure: depending on the 'weight' that is to be displayed a pressure sleeve is filled with air compressing the wrapped wrist to various degrees (see fig. 1 left). By two valves, a manometer, and an air pump the pressure level can be controlled in real time depending on the actions in the virtual environment. The control currents of the valves as well as the manometer's measurement voltage are linked to a Sensory 262 IO Card that is controlled by a Simulink model. Via TCP/IP connection the model receives trigger events from the VR in real time and sets defined pressure levels based on the values of a look-up table.

3 Experiments

Three experiments were conducted: in the experiments A and B psychophysical functions, for both the pseudo-haptic and the pneumatic feedback, were calculated; experiment C focuses on the analysis of the bimodal weight feedback.

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[4] Blender v2.49 GameEngine.

3.1 Psychophysical Scaling of Pseudo-Haptic Weight Feedback (Exp. A)

The Stevens' function [14] for the pseudo-haptic weight feedback is derived by the magnitude estimation technique. The function is defined as

$$\psi\,(I) = k * I^{a} \tag{1}$$

where the subjective magnitude of the weight perception ψ equals the product of a constant k and the objective stimulus magnitude I to the power of a. The exponent a defines the shape of the function and it has to be determined empirically.

Design of Experiment A

Five different CDR values (2, 3, 4, 5, 6) have to be rated in a paired-comparisons test. As experimental stimuli, plain grey cylinders (see fig. 1 right) are used and pseudo-weight feedback is displayed as soon as they are lifted. In each trial two cylinders are to be compared concerning their weight: one of them constitutes as a reference cylinder, which has a fixed CDR value of 2 (i.e. the lightest of all CDR settings apart from the neutral setting 1) and the other cylinder reveals the five different CDR values. To assure a similar weighing movement, the stimuli have to be raised up to a fixed height, which is indicated by a sound signal. All participants are allowed to use their own quantification scale, but they are reminded to keep it consistent throughout the experiment. No further instruction of how to interpret the feedback is given. The presentation of the stimuli is randomized. In total, 20 subjects (*ø* = 27.4 ± 8 years) took part in this experiment.

Results of Experiment A

The median values of all ratings are plotted on a log/log scaled coordinate system (see fig. 2 left). The data can be fitted well by a regression line ($R^2 = .886$). Thereby, the most interesting value is the exponent ($a_A = 1.36$) as it quantifies the relationship between the CDR value and the perceived weight: the perception of weight rises fast with increased CDR values (see figure 2 left).

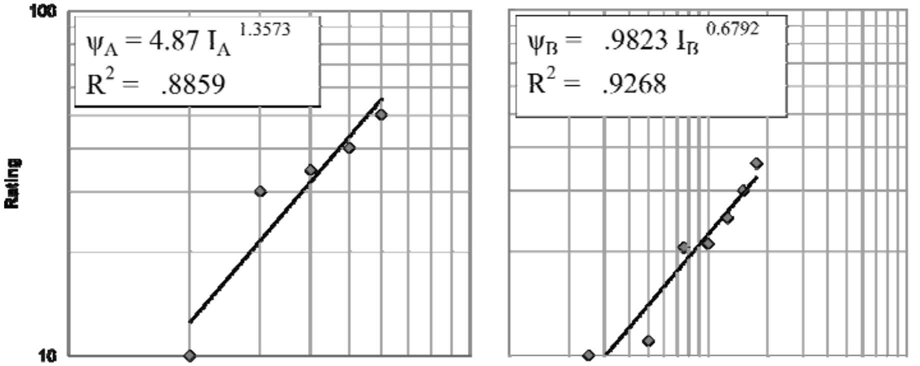

Fig. 2. Stevens' functions as derived in the experiments A (left) and B (right); log/log scale

3.2 Psychophysical Scaling of Pneumatic Weight Feedback (Exp. B)

Within the second experiment the perception of the pneumatic weight feedback is regarded and again the exponent *a* of the Stevens' function is determined.

Design of Experiment B

Just as in the experiment A, magnitude estimation is used here, too: test cylinders have to be lifted and they have to be compared to a reference cylinder. The pneumatic weight feedback of the test cylinders refers to 25, 50, 75, 100, 125, 150, and 175 mbar; the pressure level of the reference cylinder is set to 25 mbar. Again, all stimuli are presented in a randomized order and the experiment was carried out by 20 participants ($\emptyset$ = 26.3 ± 7.7 years).

Results of Experiment B

The median values are calculated for each pressure setting over all participants and trials. Just like in experiment A, the participants' ratings are plotted on a log/log scale against the objectively measured pressure values. Again, a regression line reveals a good fit ($R^2 = .927$); the exponent ($a_B = .679$) implies that the perception of weight rises much slower than the pressure of the sleeve (see figure 2 right).

3.3 Conjoint Analysis of Bimodal Weight Feedback (Exp. C)

Whereas meanwhile the psychophysical approach is rather widespread in the field of haptic display design, conjoint measurement is relatively new to this area of research. Commonly, this statistical procedure is used in marketing research in order to analyse how complex products are experienced by customers [15]. It decomposes products and assesses how important their various single elements are perceived. As products (or more generally speaking, stimuli) are typically composed of a set of different attributes that all have several distinct features (e.g. a product X with a certain colour, price, size, and flavour) a whole range of possible stimuli combinations is available. Paired comparisons of all attribute combinations have to be rated by human participants that lead to an overall ranking of all stimuli. Subsequently this ordinal ranking is used to estimate a metric value of usefulness for each attribute and these estimates are then aggregated over all participants to derive a representative result. As stated above, this method is widely used in marketing research but it is also applicable for multi-modal feedback analysis: the impact of each feedback modality on the overall percept can be extracted and quantified accordingly. Stimuli that are explored under multi-modal haptic feedback condition (e.g. weight information provided by pneumatic and pseudo-haptic feedback at the same time) have to be ranked by subjects regarding their perceived characteristics (e.g. ranking from the lightest to the heaviest stimuli). This ranking is the basis of a monotone analysis of variance, which provides a rating of usefulness for every modality that the feedback is composed of (e.g. pneumatic and pseudo-haptic visual cues); thus quantifying how each modality contributes to the overall percept.

Design of Experiment C

Four different pneumatic settings (25, 75, 125, and 175 mbar) and four CDR values (2, 3, 4, and 5) are combined so that in total 16 bimodal stimuli (e.g. 25 x 2, 25 x 3, …, 175 x 5) are presented in this experiment. In order to derive a subjective ranking of weight the participants have to classify these stimuli in rather rough categories first, namely *light, medium or heavy*. For this purpose one cylinder after the other is presented and has to be examined. Thereby, only pseudo-haptic and pneumatic weight feedback is given but no further information or explanation of how the feedback works is provided. After all 16 stimuli have been sorted, they are presented once more in order to give the test subjects the possibility to rearrange them if desired. Next the participants are instructed to rank the stimuli within each category from the lightest to the heaviest by paired comparisons. Thus, finally every participant has ranked all 16 stimuli according their weight. The data of 34 participants (ø = 26.8 ± 7.4 years) were recorded. Besides, a questionnaire was answered by everyone at the end of all trials.

Results of Experiment C

The ratings of the participants reveal a high variance. As an immediate aggregation of the data might bias the outcome a ward cluster analysis is done first. Two groups disperse very early and display a strong partition of data. Figure 3 shows both the mean values and the standard deviations of these two groups: whereas the first cluster (N = 14) relies mainly on CDR feedback (69%) and to a lesser degree on pneumatic cues (31%), the second cluster (N = 20) shows the opposite behaviour pattern (CDR cues: 18.4%, pneumatic cues 81,6%). The error bars span the range of ± 1 standard deviation.

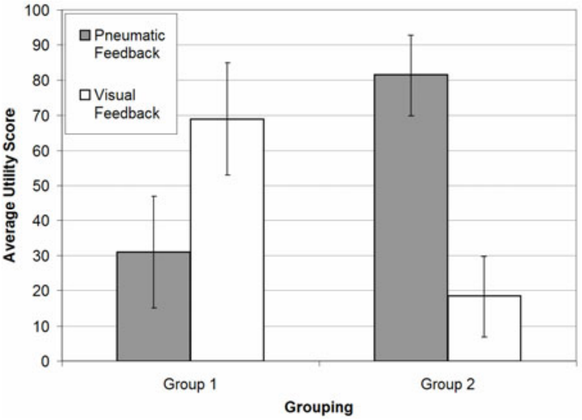

Fig. 3. Utility values of each feedback, grouped after cluster analysis

The questionnaire assesses the participants' attitude towards several aspects of bimodal weight perception. The majority (93.1 %) actually perceived a sense of weight even though they were not instructed as to how to interpret the feedback provided. The fact that 82.7 % rated this feedback as being *average* or *well* highlights the adequacy of our new feedback proposal. When comparing pneumatic and CDR feedback latter seems to be slightly less intuitive: 31 % judge CDR to be irritating with 48.3 % finding it helpful.

4 Discussion

Experiments A and B have delivered details as to how human operators perceive different magnitudes of pseudo-haptic and pneumatic feedback: the exponent of $a_A = 1.35$ for CDR based weight feedback reveals that perceived intensities aggravate faster than the corresponding objective weight. Like sucrose taste or warmth perception of small areas [14], little increases of upper CDR values lead to big perceptual changes. The pneumatic feedback approach shows a contrary effect: with an exponent of $a_B = .68$ small increases of high pressure feedback values intensify the percept only little while in low pressure ranges the perception of weight is rather sensitive, comparable to the sensation of brightness of a point source or vibrations on a finger [14]. Based on these results as well as the fact that both weight displays can be combined into one system easily it might be worth considering supplying pneumatic feedback for displaying light objects while providing CDR feedback for heavy stimuli.

In experiment C the participants displayed a split pattern of favourizing either one or the other feedback modality. The averages reported show to what extent a single modality influences the percept of each group. In both cases the participants' responses can be lead back to a combination of pneumatic as well as CDR feedback. The reason for such a split-up may be found in diverging feedback preferences when redundant haptic as well as visual cues are provided. The group membership can be ascertained perfectly by a single item classification task: do they perceive an item with CDR = 1 and pressure = 175 mbar to be light (→ group 1) or heavy (→ group 2). This would also allow to identify the personally most suitable feedback in case a single modality feedback is sufficient.

On the basis of the presented experiments the usefulness of both feedback modalities seems to be evident. While being technically simple virtual objects can be provided with weight properties to increase the immersion of virtual or telepresence scenarios. Especially in settings that require mobility these new techniques may be alternatives to current multi-DOF actuators.

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