LIMITATIONS OF HUMAN 3D-FORCE DISCRIMINATION

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ABSTRACT

Internet-based telepresence and teleaction systems require packet-based transmission of haptic data and typically generate high packet rates between operator and teleoperator. This leads to the necessity of packet rate reduction techniques. The so-called deadband approach presented earlier by the authors uses a psychophysically motivated scheme based on Weber's difference threshold (just noticable difference - JND) where force sample values are only transmitted if the change exceeds this threshold. This approach has been extended to three dimensions resulting in an additional perceptual domain - namely force direction. An experimental evaluation with human subjects was conducted in order to examine the change of the JND in 3D when force magnitude and force direction are combined. Our results show that the extension into dimensions yields to an increased JND in certain cases. Thus, higher compression ratios of haptic data and reduction in number of packets sent over the network can be reached.

1. INTRODUCTION

During recent years, telepresence and teleaction or virtual haptic teleinteraction have received increased interest in the research community and with them the communication of haptic data. Our goal is to be able to use the Internet as the communication channel in these systems because of its ubiquitous nature. Unfortunately, unpredictable time delay, delay jitter and limited bitrates are encountered in the current Internet and even very small time delays of less than 10 ms in the communication may result in instability of the aforementioned systems [1, 2, 3, 4, 5]. In order to reduce the network load, a psychophysically motivated compression approach - the so-called deadband approach - for haptic data streams has been proposed in [6]. This approach is applicable to haptic communication with 1 degree of freedom (DOF). It leads to a packet rate reduction of up to 90%. This approach has been extended to 3 DOF haptic data (deadzone approach) yielding comparable success regarding packet rate reduction [7]. The main idea is based on the fact that changes in sensor data sample values of haptic data (velocity or force) have to be transmitted only if they are perceivable by the user. To determine the magnitude of change that should trigger a packet transmission, the limitations of human perceptual abilities are exploited. It is known that the magnitude of change, which can be detected by the human perceptual system, depends on the magnitude of the given reference stimulus, whereas the fraction of the magnitude of change ΔI and the magnitude of the reference stimulus I is found to be constant over a wide stimulus range and for almost every human modality. This has been formulated into Weber's Law by Ernst Weber, a physiologist, who first discovered this relationship [8]:

$$\frac{\Delta I}{I} = k \quad \text{or} \quad \Delta I = kI \qquad (1)$$

The difference ΔI denotes the discrepancy between two stimuli, which the humans are just able to detect, and is therefore called the Just Noticeable Difference (JND). The JND for the magnitude of force lies between 7% and 10% (e.g. [9, 10, 11, 12, 13]). This fact is used in the deadband approach where force sample values are only transmitted if the change exceeds this threshold.

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2. PREVIOUS WORK

The three-dimensional extension of the deadzone approach introduces a new perceptual dimension, namely the direction of the force in three-dimensional space. Research regarding the JND for force direction is rare. Jones, Hunter and Irwin [14] report a JND of 8% for movements of the joint in the forearm. Brewer et al. [15] indicate a JND between 13% and 16.1% for the visual perception of the distance of the finger position. Keyson and Houtsma [16] found a mean orientation change threshold of 14° for a haptic point contact moving across the fingerpad of the right hand. The minimal discriminable angle was 27°. There was no difference in

threshold between left- and right-sided motions. The threshold was not dependent on the given reference direction and remained therefore constant. Similarly, the research of the Touch-HapSys project showed the human ability to discriminate directions of up to four pins moving along the tip of the index finger (e.g. [17, 18, 19]). Median thresholds ranged from 23° to 35°, with again no differences between left- and right-sided motions. Tan et al. [20] explored the threshold for force direction using a PHANToM Omni device and found the threshold to be 33°, independent of the given reference force direction. Therefore, the discrimination of force direction does not seem to fit Weber's Law, but seems rather to remain constant without dependence on the reference stimulus. The left-right directions do not seem to be different. Whether the upside-down-direction is asymmetrical, and in which scale-factor, remains unclear from previous work. The lowest threshold for force direction has been reported for motions toward the wrist, the threshold being 27° ([16]) as well as for motions away from the wrist, the threshold being 23° ([17]).

3. RESEARCH QUESTIONS

As stated above, the extension of the 1-DoF deadband approach to a corresponding 3-DoF deadzone approach yields an additional perceptual dimension - the force direction. To the authors' knowledge, so far no comprehensive psychophysical studies regarding the relationship between force magnitude and force direction have been carried out. Therefore, the precise shape of the deadzone is unknown [21]. If the JND is considered constant for all three dimensions, a spherical volume element would represent the deadzone. But it seems reasonable to assume that there is an overlap of the thresholds for force magnitude and force direction regarding human perception, which defines our research question: the determination of the deadzone's shape. Taking into account the results of [20], which state that the discrimination of force direction is independent of the reference force direction, the research domain can be reduced to two dimensions.

4. METHOD

In order to examine the shape of the deadzone mentioned above, a classical psychophysical experiment using a commercially available haptic device was conducted. The method of paired comparison applying the method of limits was adopted [8].

4.1. Hardware Setup

The SensAble PHaNTOM Omni haptic display device was used as hardware to allow efficient psychophysical evaluation. This is an affordable 6-DoF-Input (3D position and 3D orientation of the input stylus) 3-DoF-Output (3D force display) device with a reasonably good force and position resolution. For the conducted experiment, the 3-DoF force output is used to display reference and test forces in 3D space. Because force display is most accurate in the middle of the workspace of the device, the experiment was limited to this region of space by the usage of a force window. If the window, a cubical volume element in the middle of the workspace, is left by the test subjects, displayed forces are immediately released and the testing interval has to be repeated as soon as the device is back within the window. The displayed forces were applied using a 15ms linear increase and decrease phase in order to avoid giving the test subjects additional cues by way of the sudden on and off switch impulses.

4.2. Experimental Setup

4.2.1. Stimuli

Three reference stimulus magnitudes (1.0N, 1.5N and 2.0N) and eight perturbation directions ($0°$, $45°$, $90°$, $135°$, $180°$, $225°$, $270°$, and $315°$) as shown in Figure 1 were chosen. All pertubation directions lie in one plane with the reference stimuli. For the reference vector with medium magnitude (1.5 N), the orthogonal plane was additionally tested in order to confirm the results of Tan et al.[20]. The comparison stimulus is a vectorial addition of the reference stimulus and a perturbation vector. This perturbation vector points in the perturbation direction and its magnitude is defined by a percentage b of the respective reference stimulus magnitude. b is in a range from 0% to 60% with steps of 5%. For the directions of α = 0° and α = $180°$ b is reduced to a range from 0% to 20% with steps of 5%, as in this case b influences only a change in force magnitude and leaves the direction untouched. It is well known that the JND for force magnitude lies between 7% and 10%, which justifies the reduction of the range for these two angles. Since the orthogonal plane for the middle reference vector served as an additional check up, here a reduced range of b was set from 5% to 55% in steps of 10%.

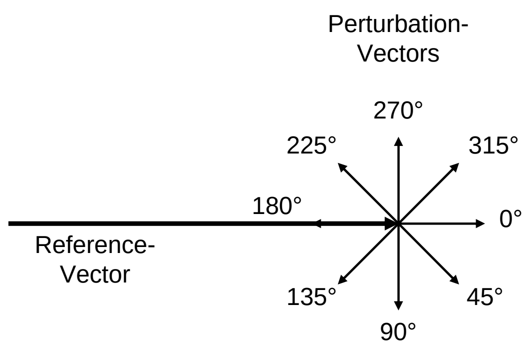

Fig. 1. Standard stimulus with directions of perturbation vectors.

4.2.2. Procedure

Subjects are seated in front of the PHaNTOM Omni device and instructed to hold the stylus of the device loosely in their dominant hand and to maintain the same hand position for the duration of the experimental session. In order to ensure that the subjects only consider the haptic modality, they are blindfolded during the experimental evaluation.

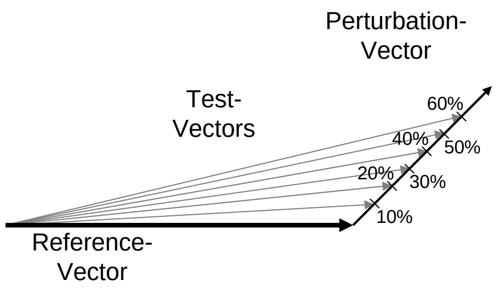

Fig. 2. Steps of change for an exemplary reference and perturbation vector.

For each reference stimulus, only one half of the perturbation plane is tested, hence each subject performs only up to five directions of α within the range from $0°$ to $180°$ or from $180°$ to $360°$ (see Figure 1). After a random selection of the field of activity, the perturbation directions are put in randomized order as well. Additionally, the percentage values b defining the perturbation magnitude are divided into two disjoint groups, as shown in Table 1. For each perturbation angle, one test-group is randomly selected. Thus, it is possible to keep a 5% stepsize for b in total and simultaneously the number of force pairs per subjects is reduced by 50%. The selected perturbation angles and the perturbation magnitudes form the perturbation vectors. They are used to compute the respective test/comparison vectors by vectorial addition of the reference and perturbation vector, as can be seen in Figure 2. The subjects are presented subsequent pairs of two force stimuli consisting of a reference vector and a test/comparison vector.

Perturbation-Angle	Test-Group 1	Test-Group 2
$45°$, $90°$, $135°$	0, 5, 15, 25, 35, 45, 55 %	0, 10, 20, 30, 40, 50, 60 %
$0°$, $180°$	0, 5, 15 %	0, 10, 20 %
$45°$, $90°$, $135°$ (orthogonal plane)	5, 25, 45 %	15, 35, 55 %

Table 1. Partitioning of Test-Vectors

A two-forced-choice alternative paradigm (paired comparison) applying the up-and-down or staircase method was adopted [8]. Starting with the highest possible value of b (maximal perturbation), the perturbation magnitude is progressively decreased by the stated steps. After presenting the pair of force stimuli to the subjects, they are asked to indicate whether the two stimuli felt the same or different. If desired the presentation of the force pairs is repeated. At the point where the subject's response changes from "different" to "same", the experiment starts in a new pass applying the smallest possible value of b (0% - minimal perturbation) and ascending direction. In this case, changing of the subject's response from "same" to "different" leads to a termination of the test sequence. This up-and-down method is repeated for every perturbation angle until all JND boundaries are detected.

At the end, a questionnaire including a query of biographical data is filled out by each subject. This included details such as age, gender, handedness, amount of previous experience with the PHaNTOM Omni device and whether they play a musical instrument, and if so, which instrument and for how long they have played it. The latter is done in order to control possible high haptic discrimination abilities of stringed instrument players.

4.2.3. Subjects

4 female and 13 male subjects participated in this evaluation. Their age ranges from 23 to 59 years (averaged 31 years). 13 of them are right-handed and 4 of them left-handed. Most of the subjects (n = 12) have no or little previous experience with the PHaNTOM Omni device and n = 5 state to have a middle to very high amount of experience with this device. 6 of the subjects report playing a stringed instrument at present or previously for 6.7 years on average. Before and during the experiments, all subjects had no information about the intentions or hypotheses of the experiments. Afterwards, they received a full explanation. Their personal data was recorded anonymously.

5. RESULTS

For every perturbation direction the reference-comparison force pairs, where the subject's response changed from "different" to "same" for a descending, or from "same" to "different" in case of a ascending series is tracked. The corresponding JND values are computed by taking the average magnitudes of these test vectors. Cases where the response was "different" for minimal perturbation and/or the response was "same" for maxmimal perturbation are excluded from further analysis.

Because the data for the orthogonal plane served as an additional check up (see above), they were generally not included in the analysis except when explicitly mentioned.

Altogether N = 499 pairs of standard and test stimuli were utilized. None of the collected questionnaire data is correlated

with the dependent variable. Hence, the values of the questionnaire data can be considered independent of the JND.

The JND served as dependent variable, influenced by three factors: the standard stimulus (three levels 1 N, 1.5 N and 2 N), direction of perturbation and intensity of perturbation (see Figure 1).

5.1. Influence of Standard Stimuli, Perturbation Direction and Intensity

In order to examine whether standard stimuli, perturbation direction and intensity have an impact on the dependent variable (measured JND), a three-factorial analysis of variance was conducted. The overall effect of these variables turned out to be significant, F(29,47) = 9.17, $p < .000$ [1]. Considered in detail, the differences regarding the three levels 1 N (average JND M = 20.15% [2]), 1.5 N (M = 17.32%) and 2 N (M = 16.59%) were significant, F(2,47) = 6.183, p = .002. The effect size which indicates the magnitude of an effect lies in the lower mid-range (η^2 = 0.362). The Student-Newman-Keuls-Test as a post-hoc test revealed that the level 1 N was different to the other two, whereas the levels 1.5 N and 2 N did not differ. This result is somewhat surprising because there should be no difference between the standard stimulus levels. The slightly increased average JND of the standard vector of 1 N suggests that this vector operates near the perceptual limit where Weber's Law hardly applies. For the perturbation side, no significant difference between the left perturbation plane (from 180° to 360°, see Figure 1) (M = 17.294%) and the right perturbation plane (from 0° to 180°, see Figure 1) (M = 18.745%) could be found, F(1,469) = 2.798, p = .095. This lacking effect was as predicted.

Regarding the perturbation direction, the means of the JND were as follows: M ($0°$) = 10.671%, M ($45°$) = 25.427%, M ($90°$) = 21.852%, M ($135°$) = 22.042% and M ($180°$) = 10.107%. These differences turned out to be significant, F(4,469) = 53.267, $p < .000$. The Student-Newman-Keuls-Test showed that $0°$ was indistinguishable from $180°$, $90°$ was indistinguishable from $135°$, whereas these two groups and the absolute angle of $45°$ did differ. In order to determine how well the JND for pure differences in force magnitude matched the JND from 7% to 10% reported in the literature, a one-sample t-test for the midpoint between the angles of $0°$ and $180°$ (M = 10.596%, N = 193 pairs) against 10% was conducted. The results showed that the JND for the two angles did not differ from 10%, t(192) = 1.643, p = .102 [3]. This means that the JND surveyed here resembles that one already reported in the literature [9, 10, 11, 12, 13].

In respect of perturbation intensity for the two disjoint groups (see Table 1), a two-sample t-test concerning the JND for Test-Group 1 (M = 18.621%) versus the JND for Test-Group 2 (M = 19.493%) was conducted. For this analysis, the values for the orthogonal plane (standard vector 1.5 N) were included (N = 601 pairs altogether). No significant difference was found, t(599) = -0.936, p = .350 [4], which means that the two test-groups in Table 1 can be combined to compute the overall JND.

5.2. Comparison of the Orthogonal Plane with the Reference Plane for the Standard Vector of 1.5 N

It was hypothesized based on [20], that the perturbation direction is independent of the reference stimulus direction. Therefore, the orthogonal plane, which was realized for the standard vector of 1.5 N, should not differ from the reference plane. To test this hypothesis, a two-factorial analysis of variance was conducted. The independent variables were the absolute values of angle including the levels $45°$, $90°$, and $135°$, and the plane dimension (standard vs. orthogonal). The dependent variable was the measured JND across subjects. N = 204 pairs of standard and reference stimuli were analyzed.

The means of the JND were M($45°$) = 25.33%, M($90°$) = 20.88% and M($135°$) = 19.56% in the condition with the standard plane, and M($45°$) = 23.35%, M($90°$) = 23.27% and M($135°$) = 23.27% when the orthogonal plane was displayed. These mean-differences between the plane dimensions turned out not to be significant, F(1,198) = 0.81, p = .37. This means, the orthogonal plane does not differ from the reference plane as predicted.

5.3. Shape of the Deadzone

The main interest of this study was the determination of the deadzone's shape. Former analyses showed that the JNDs of the reference stimulus of 1 N differs from those of the other two reference stimuli, the JNDs of the right perturbation equals that of the left one, and the JNDs of $0°$ and $180°$, as well as $90°$, $135°$, $225°$ and $270°$ can be combined because of no differences. Therefore, the JNDs were averaged according to these results across all subjects. Figure 3 shows the JNDs concerning the perturbation-vectors along with the

[1] In analyses of variance the F-test is used in order to test the statistical significance of a result. F denotes the x-coordinate value of the F-distribution. Numbers in parentheses indicate the degrees of freedom of the numerator and the denominator, respectively, in order to determine the exact shape of the F-distribution, which means a correction regarding the sample size. p is the corresponding probability of error to the value of F. When p is smaller than the significance level (5% in this case), the result turns out to be significant, i.e. it is not attributable to chance and an effect can be assumed. For more details, see [22].

[2] M is the abbreviation for the arithmetic mean

[3] The one-sample t-test is used when a result is tested against a constant value. The value of t indicates the abscissa-value of the t-distribution. The number in parentheses denotes the degrees of freedom in order to determine the exact function of the t-distribution and in order to correct the result in regard of the sample size. p specifies the corresponding probability of error to the value of t, see [22].

[4] The two-sample t-test is used when comparing two samples in order to find out whether the difference is due to chance. The number in parentheses indicates the degrees of freedom. p is the corresponding probability of error, see [22].

shape of the deadzone in two dimensions. The deadzone for the standard vector 1 N is plotted as a dashed line, the solid line represents the deadzone for the standard vectors 1.5 N and 2 N. As can be seen from the Figure, the JNDs for pure changes in force magnitude (perturbation-vectors of 0° and 180°) are smaller than those for changes in force magnitude and force direction as predicted. Moreover, the JNDs for this case match the JNDs of 10% reported in the literature. There seems to be an overlap of the perception of force magnitude and force direction and the symmetry is given as predicted. Because of the confirmation of the results of [20], namely no difference between the standard and the orthogonal plane regarding human discrimination abilities, the three-dimensional deadzone can be computed by rotation of the two-dimensional shape shown in Figure 3 along the principal axis.

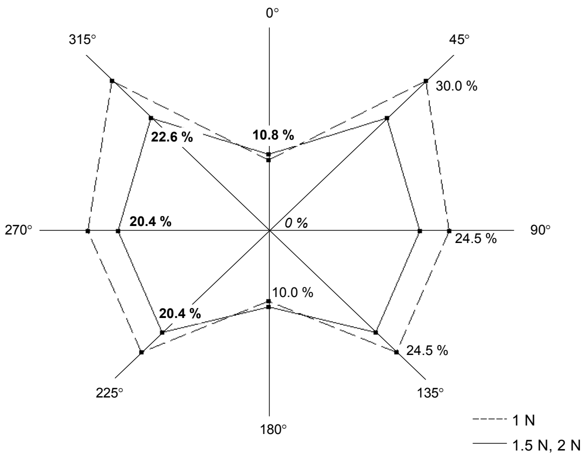

Fig. 3. JNDs and 2D-deadzones for the reference vector with a force magnitude of 1 N (boldface and dashed line) and the combined reference vectors of force magnitude vectors of 1.5 N and 2 N (solid line) as a function of perturbation direction.

6. CONCLUSIONS AND FUTURE WORK

The deadband and the deadzone approach, respectively, are transmission and compression schemes for haptic data which exploit the fact that humans' ability to discriminate stimuli is limited. It was examined what threshold results when two perceptual dimensions, namely force magnitude and force direction, are combined as in the deadzone approach. It has been shown that the formerly assumed spherical deadzone [7] is a very conservative assumption when looking at the empirical results of this paper. When force direction and force magnitude are varied together, the JND that humans detect increases up to 30% (see Figure 3), so that the compression of the haptic data can be adjusted and further increased. Thus, the packet rate can be further reduced. However, the JND turned out to be dependent of the given standard stimulus. To improve the accuracy of the deadzone approach, further studies covering a larger range of reference vectors have to be done.

Furthermore, it could be confirmed that the deadzone considered in a two-dimensional plane did not differ in respect of the third dimension, therefore no special cases regarding the three-dimensional deadzone have to be taken into account. However, only the orthogonal plane was evaluated here, for confirmation purposes more research has to be done with more than one plane concerning the third dimension.

The deadzone's shape showed a tendency for stretching towards the left-right-sides compared to the up-down-direction, which indicates an overlap of the perception of changes in force magnitude and force direction. For the precise shape of the deadzone, future work should aim to test more perturbation-vectors experimentally to determine the curve fit for the shape of the deadzone.

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