Evaluation of Vibrotactile Feedback to the Human Arm

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ABSTRACT

This paper investigates the main factors influencing the design of a vibrotactile feedback device for the human arm. Beside the determination of hardware settings, e.g. vibration motor type (pancake or cylindrical) and intensity threshold, this paper concentrates on the determination of spatial acuity and the division of the arm's perimeter into sectors which can be distinguished reliably. The realisation of this research is to present collision feedback to the human arm operating in a Virtual Reality system for assembly verification.

Keywords: haptic feedback, vibrotactile feedback, evaluation study, virtual assembly verification

1 INTRODUCTION

Using haptic feedback in Virtual Reality (VR) systems is still an actual and vital research topic [2]. Additional to the visual and auditory feedback the haptic modality plays an important role when manipulating objects in the virtual world. A lot of work is done to present the interaction forces/torques between the manipulated object and the virtual model to the operator [7] and [1].

The goal of haptic feedback in VR has to be a fullbody feedback, due to the fact, that the human haptic sensory is also distributed over the whole body. There is some research adressing the topic of full-body distributed feedback. Considering the human arm basically two ways to generate a haptic feedback exist: force feedback (e.g. exoskeleton [5]) and vibration feedback [12]. While force feedback provide proprioceptive stimuli, vibration devices produce more tactile feedback.

One application domain of VR systems is the virtual product creation process in industry, namely the automotive or aerospace industry. These industries are pushing VR technology because of the complexity of their products and the high costs of hardware prototypes. An important application of VR is the virtual assembly verification, with its goal to verify the production feasibility and maintainability of a product [11]. Using VR technology for these studies will

1. improve the design of machines in respect of maintainability
2. and speed up the development process.

At the DLR, a VR system for virtual assembly verification has been set up [6], providing 3D visual feedback throuh a 3D back projection or a Head-Mounted Display and 6D force/torque feedback using the DLR light-weight-robot [10], see Fig. 1. During the assembly, collision forces are calculated and displayed to the operator through the haptic interface.

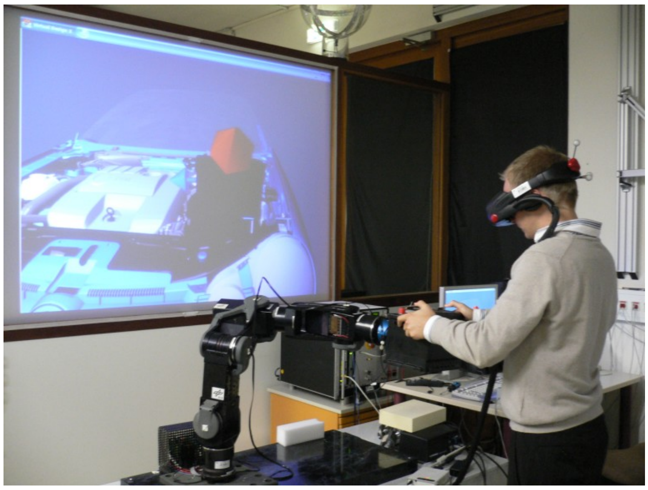

Figure 1: VR system for virtual assembly verification

2 PROBLEM DESCRIPTION

At the DLR, forces between the movable object and the virtual environment are computed in the haptic simulation and displayed by the light-weight-robot. The operators' arms are not yet considered. For a more realistic design of the application, it is essential to extend the system with haptic feedback to the forearms. This means that if the operators' arms collide with an object of the VR, the collision situation will be computed and displayed through the vibrotactile feedback device. For this, a model of the operators' arms must be implemented and integrated into the VR. In the real world, the arms will be tracked and their movements will be transfered to the VR. This paper investigates the implementation and the design of such a vibrotactile feedback device.

Several factors influence the immersive impression of a collision in the virtual environment. Factors investigated in this paper are:

1. Type of vibration motor (pancake or cylindrical)
2. Number of vibration motors per interaction point
3. Alignment and distances of the vibration motors
4. Intensity of stimuli (by varying the voltage)

A prototype (see Fig. 4), enabling an easy and fast changing of the parameters, was developed.

Cholewiak and Collins [3] stated, that tactile acuity has been extensively investigated for pressure stimuli whereas vibrotactile

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stimulation has not. In the nineteenth century, Weber [13] introduced the two-point discrimination test. The two-point discrimination test detects how long the distance between two points has to be for that they can be perceived as two points and not as one. Many investigations of the last time based on this test, but for all that less results and experience with vibrotactile acuity are available. As haptic feedback and haptic stimulation are subjective perceptions depending on the bodies location, important factors for a hardware design must be determined individually for the desired application. Therefore, this paper perpetuates the spatial acuity under the aspect to obtain the best possible accuracy of given patterns.

3 Hardware

Basically there are two types of vibration motors: pancake and cylindrical motor (see Fig. 2). Normally, they are both used in mobile phones. As a special development of vibration motors was not intended, they present a good possibility to design a low priced device.

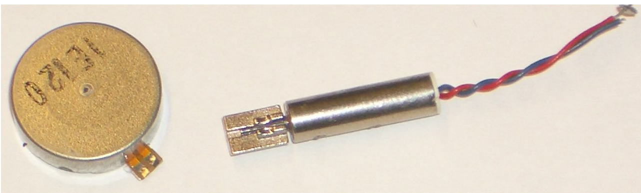

Figure 2: Pancake motor (left) and cylindrical motor (right)

Both types generate the vibration by rotating an unbalanced mass. The main difference between these two motor types is the orientation of their rotating axis. The pancake motor with a diameter of 13 mm rotates in a plane parallel to the surface whereas the cylindrical motor with a diameter of 4 mm rotates in a plane orthogonal to the surface. Consequently, pancake motors cause shear forces to the skin and cylindrical motors cause forces orthogonal to the skin. While the pancake motors are already in a housing, the cylindrical motors were mounted in an aluminium tube avoiding to touch the rotating mass.

Since the perceived magnitude of the vibration mainly depends on the frequency, a voltage-frequency-chart was recorded for both motor types. Maximum stimulation of skin mechanoreceptors occurs at a frequency of about 250 Hz [3]. This is in accordance with the results of Murray et al. [8].

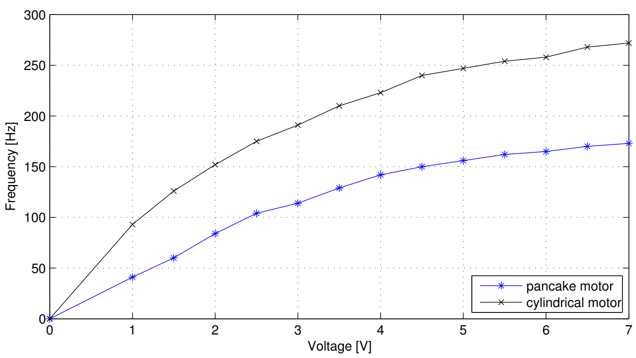

Figure 3: Frequency of pancake and cylindrical motors against voltage

As shown in Fig. 3, the cylindrical motor rotates in a frequency closer to the desired frequency and will therefor probably perform a better impression than the pancake motors.

To allow for a flexible and fast attachment of the motors, velcro fastening in combination with an elastic cuff is used. The parallel port of the computer is used to activate the motors. As the output pins of the parallel interface don't provide enough power to run the motors directly, a Darlington-Array-Integrated-Circuit was soldered up. A software enables to send a control pulse to several motors or to choose one of the implemented patterns (sequence of different motors).

4 Description of Experiments

The accomplishment of experiments was separated in two parts: in the first part, the motor types and their features were assessed, in the second part, the spatial acuity and the accurate recognition of stimuli were tested. The experiments are described in detail in 4.2 and 4.3.

4.1 Participants

All eleven subjects participating in the experiments were trainees or employees of the German Aerospace Center (DLR). Some of them were experienced with haptic devices and force feedback. Their ages range from 21 to 34 years. Two of them were female. On average, the arm-lenght is 26 cm and the average perimeter is 26 cm, too.

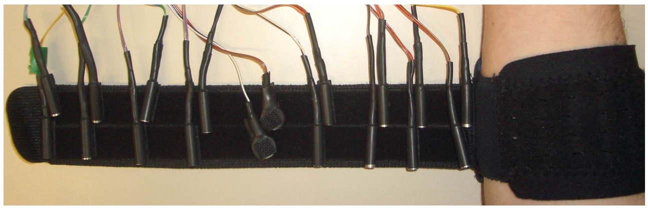

Figure 4: Prototype of the vibrotactile haptic feedback device.

4.2 Experiments part one – motor types

The goal of the first part of the experiments is to evaluate the two different motor types and their features.

At first, four different settings were applied to the top side of the subject's forearm close to the wrist: one pancake motor, one cylindrical motor, two pancake motors and two cylindrical motors. The duration of each stimulation was an impulse of 400 ms. This task was intended to find out which motor is suitable to display a collision and furthermore to find out the effect the number of motors has. The subjects were asked to sort the possibilities from 1 (worst) to 4 (best).

Secondly, the necessary or rather desired intensity of vibration was determined. The intensity was increased step by step (one step = one volt). The subjects had to tell as soon as they started to feel the stimuli, at what stage the stimuli was convenient and at what stage the stimuli was unpleasant. Each stimuli lasted 400 ms with recesses of 2 seconds.

Thirdly, the influence of rotation direction was analysed. Depending on the alignment, the motors rotated either in the same direction or in opposite directions. In order to find out whether an interaction could affect the impression of contact, two motors were fixed to the cuff. In the first run, both motors were orientated the same way, in the second run one of the motors was turned (pancake: upside down, cylindrical: 180° rotated). If the subjects had recognised a difference, it was annotated whether they prefered synchronous or opposite rotation directions.

4.3 Experiments part two – spatial acuity

In the second part of the experiments, the spatial resolution (acuity) and the accurate recognition of vibrotactile stimulation were assessed. The intention of these experiments was to figure out a reasonable division of the arm's perimeter in distinguishable areas. The arm was divided into three regions: close to the wrist, close to the elbow and close to the upper arm (see Fig. 5). The experiments were conducted for each of them.

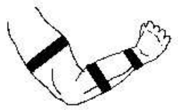

Figure 5: Postitions of the three different regions

Furthermore, three configurations of motor alignment were analysed (see Fig. 6). In the first run only four areas were applied to the subject's arm by sticking two motors side by side on the upside, the right side, underside and the left side each. In the second run the perimeter was divided into eight areas so that the motors were fixed to the cuff in 45° steps. The last configuration divided the perimeter into six areas with an angle of 60° between the motors.

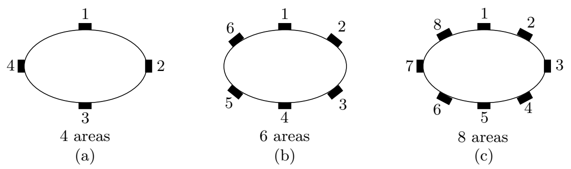

Figure 6: Configurations of motor alignment

In any run, predefined sequences of motor activation were passed. For example, motor 1,3,2,4 (Fig. 6 .(a)), 1,3,6,4 (Fig. 6.(b)) or 3,8,5,1 (Fig. 6.(c)) are such patterns. Their order was permutated to suppress the influence of learning effects. The pulse duration was set to 400 ms with pauses of the same duration. The subject was instructed to successively write down the felt positions by marking them on a figure of the arm. In addition they had to write down their impression of the three different configurations and to give their subjective judgement upon it.

5 Results

The results of the two different motor types and their features are discussed in section 5.1. In section 5.2 the results of the spatial acuity and the accurate recognition of vibrotactile stimulation are shown.

5.1 Results of part one – motor types

Fig. 7 shows the average rating of the two different motor types and the variation of their number. As expected, the cylindrical motors performed better than the pancake motors because pancake motors cause shear forces to the skin and cylindrical motors cause forces orthogonal to the skin. This result corresponds to the investigation from E. Piateski and L. Jones [9].

Results of the vibration intensity experiment can be seen in Fig. 8. It demonstrates the average values of the three interesting values "start to feel the stimuli", "the stimuli is convenient" and "the stimuli is unpleasant". A reasonable value for the voltage is about 4 volts. According to Fig. 3, the cylindrical motor rotates with a frequency of about 225 Hz. As the maximum stimulation of

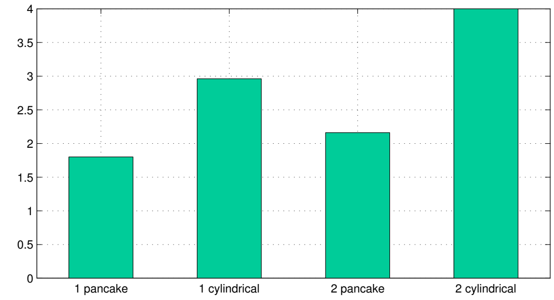

Figure 7: Rating of the different motor settings (0=worst, 4=best)

mechanoreceptors of the skin occurs at a frequency of about 250 Hz [3], the cylindrical motor performs better.

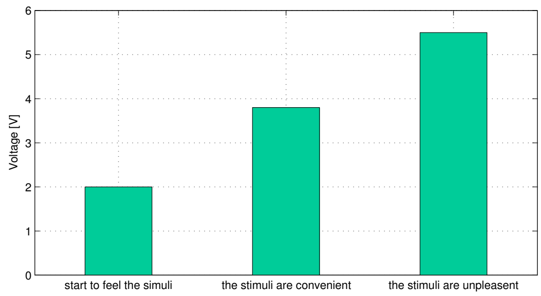

Figure 8: Evaluation of vibration intensity

The result of the experiment investigating the effect of motor rotation directions is shown in table 1.

	difference noticed	opposite direct. preferred	synchronous direct. preferred
pancake motor	54 % (6 of 11)	17 % (1 of 6)	83 % (5 of 6)
cylindrical motor	82 % (9 of 11)	78 % (7 of 9)	12 % (2 of 9)

Table 1: Recognition of rotation difference

A difference in whether the pancake motors rotate in synchronous or in opposite directions was detected by 54% of the subjects. 83% of them judged the synchronous rotation direction better. As for the cylindrical motors, significantly more, namely 82% of the subjects recognised a difference. 78% of them prefered opposite rotation direction stating that the stimulation was clearer and that it felt more comfortable.

5.2 Results of part two – spatial acuity

An overview of the results of spatial resolution and accurate recognition (spatial acuity) of vibrotactile stimulation is given in Fig. 9.

Three different configurations have to be considered:

(a) 4 areas:
Remarkable is the hit rate of 97% – 98% in the case of only four areas on the perimeter. Obviously it is no problem to distinguish four areas. However, an interesting notice is that the hit rate dropped down to 80% – 91% when the motors with number 1, 2, 3, 4 (see Fig. 6.(a)) were alternately activated

but all eight areas were attached to the cuff and the subjects didn't know that only these four motors are activated. Often, the direct neighbouring motors were marked.

Regardless of the region (wrist, elbow, upperarm), the hit rate is nearly the same.

(b) 6 areas:
A hit rate range from 85% – 95% was obtained. The result of the upperarm showing 95% correct answers is the best value in the experiments with 6 areas. This stand to reason because of the bigger perimeter of the upperarm. Here, the point to point distances of motors is increased.

(c) 8 areas:
Less than 75% marked positions were correct. At the region close to the wrist, 72% of the answers were correct and 74% correct answers were obtained in the region close to the elbow. Considerably more correct answers, i.e. 89%, show again, that the bigger perimeter enlarge the distances between the motors and that it is therefore easier to distinguish the different motors.

Regarding these hit rates, it is the question whether the better spatial resolution justifies the additional expenses and particularly the less reliable recognition rate.

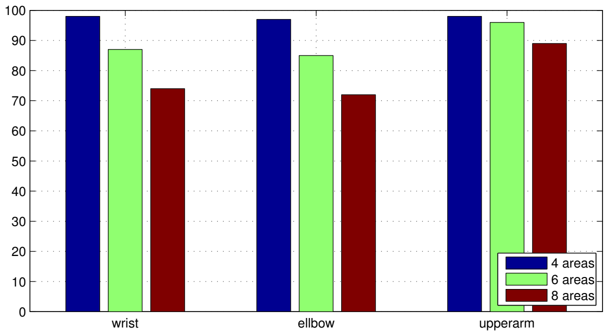

Figure 9: Correct recognition of motor activation sequences in percent

All subjects were in complete agreement that the configuration with four areas is too imprecise. They prefered the configuration with six areas because of three reasons:

1. six areas are covering the whole perimeter without overlapping of areas.
2. none of the motors is situated on bones (ulna and radius). This was experienced to feel better by the majority of subjects.
3. six areas are good to distinguish, whereas eight areas are not. The subjects were convinced that visual assistance helps to differ 8 areas, but anyway, in their opinion, eight areas are not obligatory.

One of the subjects proposed to use only four motor groups but to generate the areas 2, 4, 6, 8 (see Fig. 6.(c)) by activating the neigbhouring motors at the same time. To get the impression of a collision at position 4 for example, the motors 3 and 5 must be activated. In a following experiment, this couldn't be confirmed: the subjects did not feel a superposition of stimuli at the postiton of motor 4, instead of that, they felt the two areas at the same time.

6 Conclusions

In this paper, the hardware setup and the spatial acuity have been investigated in order to design a vibrotactile haptic feedback device for the human arm.

Although results of investigations for example like two-point discrimination on the arm is well known, such values are not necessarily the basis for the design of a haptic feedback device. Haptic feedback and haptic stimulation are subjective perceptions and therefore the hardware design parameters must be determined individually for the desired application.

This paper focused on the choice of the best vibration motor type plus its activation and on the investigation of the division of the arm's perimeter into sectors that can be distinguished reliably.

Considering the motortype the cylindrical vibration motor turns out to provide a better feedback. This result was expected, due to the fact, that this motor provides a frequency closer to the 250 Hz. Evaluating the vibration intensity a value of about 4 V, i.e. 225 Hz, using two motors in opposite rotation direction was rated highest.

Although a spatial acuity of the arm between 2 and 3 cm was determined by the two-point discrimination [4], it is obviously very difficult to localise the stimulation precisely and to track the given sequence of motor activation. If eight areas were in use, a minimum distance of about 2,8 cm between the motors resulted. While this value is inside the range of the two-point spatial acuity, the subjects' accuracy was quite unreliable.

The division of the arm's perimeter into six sectors is a good compromise between correct responses and the resolution to display a collision. With about 3,3 cm space between the motors, the critical threshold of 3 cm is exceeded but even so, the hit rate was not 100%.

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