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SYSTEMATIC CONSIDERATION OF HAPTIC PERCEPTION IN THE DESIGN OF TASK-SPECIFIC HAPTIC SYSTEMS

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Abstract: *This work proposes a new additional step in the development of task-specific haptic teleoperation systems. This step termed* interaction analysis *leads to a better insight for relevant requirements for the design of the system. This is based on an analysis of human force perception with respect to external influencing factors and the coupling of the perception of forces and kinematic quantities by the mechanical impedance of the user. Furthermore, the concept of haptic transparency is extended to form a evaluation criterion with consideration of haptic perception capabilities.*

Keywords: *haptic systems, design methodology, haptic perception, transparency*

Introduction

Haptic systems gain more and more importance in medical areas in the last few years. Applications include sensory substitution for the visual impaired, diagnostic and rehabilitation applications [1], simulators [2] and surgical telepresence systems [3]. Such systems need to be carefully designed in respect to the intended application and to the capabilities of the human user. Since the human perception and interaction capabilities are highly specialized with respect to bandwidth, resolution and overload capacity, the design of high-fidelity teleoperation systems encounters challenges regarding the design of sensors, actuators and kinematics.
Since present developments do not fulfill all conditions imposed by human interaction and perception capabilities, this work aims to reduce requirements in the design of haptic systems by a systematic consideration of perception parameters and the design process of haptic systems. Latter is derived from common mechatronic design processes like the *V- or waterfall-model* [4].

Methods

To obtain a general applicable approach that can be integrated in such common processes, the human ability to detect and differentiate forces, the relation between the perception of forces and kinematic stimuli (deflections, velocities, accelerations) and evaluation criteria for haptic systems were investigated [5].

Human Force Perception. Absolute and differential thresholds *(JND)* of the perception of vibrotactile forces were measured with an adaptive psychometric procedure (*Adaptive Staircase* with 1down-2up-progression rule, 3 IFC paradigm [6]) using a specific designed measurement setup.

Relation between the perception of forces and kinematic quantities. The hypothesis of not only a mechanical coupling between these quantities, but also a perceptual coupling via the mechanical impedance $\underline{z}$ as defined in eq. (1) based on the force $\underline{f}$ and the velocity $\underline{v}$ was investigated.

$$\underline{z} = \frac{\underline{F}}{\underline{v}} \tag{1}$$

To test the hypothesis, absolute thresholds for the detection of deflections ξ' were derived according to eq. (2) and compared to the values given in [7], where deflection thresholds are investigated for a similar contact situation (concave contactor with a diameter of 19 mm, measured at the fingertip). User impedances were calculated from a network parameter model [8].

$$\xi' = \frac{F_{Threshold}}{|j\omega \cdot \underline{z}|} \tag{2}$$

Influencing factors. Known influencing factors on haptic perception were chosen with respect to the design process. Despite frequency and contact force, temperature, age and fingertip size were evaluated as independent variables. Multiple one-way ANOVAs were performed to assess the influence of these factors on the absolute and differential force perception threshold. All significant variables were further analyzed with a corresponding N-way ANOVA.

Evaluation critria. Based on recent works on the evaluation of haptic systems [9], haptic transparency and control stability were identified as the most relevant evaluation criteria for teleoperation systems.

Results

Human Force Perception. The measured differential thresholds are given in fig. 1. They can be directly interpreted as the admissible reproducibility error of forces in an haptic system. Absolute thresholds (given in [5]) can be directly interpreted as the necessary resolution of sensing and actuating components of the haptic system.

Relation between the perception of forces and kinematic quantities. The hypothesis stated in eq. (2) could be verified, since perception curves showed good agreement. Basic significance tests (mean of measured thresholds in the

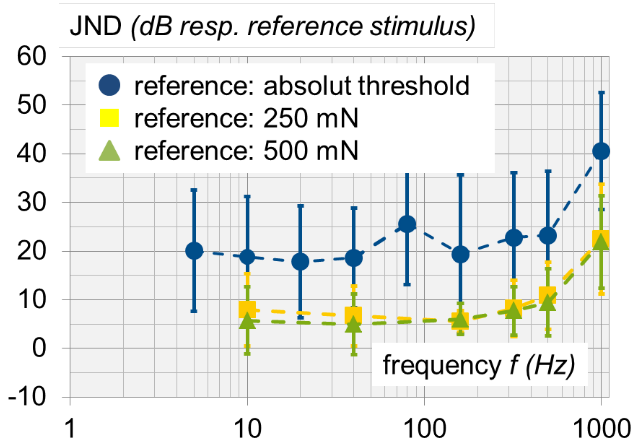

Figure 1: *Just noticeable differences for human force perception measured with respect to three different reference stimulus intensities. Results are based on experiments with 36 (250 and 500 mN reference) and 29 test subjects (absolute threshold reference). They comply with Weber's Law, stating higher JNDs when reference stimuli approach the absolute perception threshold.*

$\pm 1\sigma$ bounds of the calculated thresholds) showed a significant relationship.

Influencing factors. All data was evaluated on a $\alpha = 0.05$ significance level. Frequency proved to be a highly significant influencing factor on both absolute (F(8,86) = 12.92, p<0.01) and differential (F(8,135) = 4,09, p< 0,01) threshold. Test persons age (age group 20-30 vs. age group 40-50) proved to be a significant factor on the absolute threshold (F(1,10) = 5,20, p = 0,026). Fingertip sizes showed significant influence on the different JNDs measured, while no effect of contact force and temperature could be measured.

Evaluation criteria. Based on the results above, the concept of haptic transparency could be extended to incorporate the perception capabilities of the user. For a teleoperation system, the admissible error $|\underline{E}_T|$ for displaying the remote impedance $\underline{z}_e$ as the local impedance $\underline{z}_t$ can be expressed by eq. (3) and limited by the differential threshold for arbitrary mechanical impedances. A complete derivation is given in [5].

$$|\underline{E}_T| = \left| \frac{\underline{z}t - \max\left(\underline{z}_e, \underline{z}_{User}\right)}{\max\left(\underline{z}_e, \underline{z}_{User}\right)} \right| \leq JND(\underline{z}) \qquad (3)$$

Discussion

Based on the results, an additional step named *interaction analysis* in the development of haptic systems is proposed. This step should include a detailed analysis of the intended user group, especially with respect to age groups, and the definition of a suitable grip for the interaction with the haptic system. This grip should be chosen with respect to a high mechanical impedance and little operator fatigue. Based on this grip, the mechanical impedance of the user and perception thresholds for deflections should be derived. From them, force perception parameters can be calculated based on eq. (2). Perception parameters like absolute and differential thresholds can be used in the requirement engineering of the system, as well as the mechanical impedance representing the mechanical load of the user to the system.
For system evaluation, control stability and haptic transparency can be used as conflicting optimization criteria. With an appropriate modeling technique for all system components such as concentrated network parameters, these criteria can be analyzed frequency dependent and components can be optimized explicitly in the relevant bandwidth segments. Since perception parameters are considered in the requirements and the definition of the allowable error of haptic transparency $|\underline{E}_T|$, see eq. (3), no user evaluation is necessary in the technical optimization of the system.
To evaluate the purpose of the system, additional tests regarding task completion time or mental workload of the user can be helpful. If possible, tests and possible output should be defined in the interaction analysis as well.
The proposed methodology should lead to faster and more accurate development of high-fidelity, task-specific haptic teleoperation systems.

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