Combining Vibrotactile and Kinaesthetic Cues in Haptic Volume Visualization

Karljohan Lundin Palmerius*
C-Research
Linköping University, Sweden

ABSTRACT

Haptics has in earlier work shown the potential to assist in the understanding of an otherwise overwhelming amount of information in scientific and medical visualization. In the typical scientific data, with many different properties such as pressure, temperature, strain, etc, the user is required to switch between what data to represent through the haptic feedback. In this paper we explore the possibility to simultaneously represent, in a comprehensive way, more than one property through the haptic feedback by dividing the feedback into the two components of the haptic sense. Two vibrotactile metaphors for scalar data are described, roughness and transition cue, that can be used in combination with a kinaesthetic representation of either scalar or vector data. The paper also presents an evaluation that shows that the individual cues from the two haptic metaphors can be discriminated, and that the combined feedback can be used to find combinations of features in data.

Index Terms: H.1.2 [MODELS AND PRINCIPLES]: User/Machine Systems—Human factors I.3.6 [Computer Graphics]: Methodology and Techniques—Interaction techniques; H.5.2 [Information Interfaces and Presentation]: User Interfaces—Haptic I/O; I.3.8 [Computer Graphics]: Applications—Scientific Visualization

1 INTRODUCTION

Haptic feedback has become a powerful addition to the visual sense in many areas of computer graphics and applications. In the areas of scientific and medical visualization the sense of touch has the potential to assist in the understanding of an otherwise overwhelming amount of information in the typical data set. The haptic modality then provides an additional channel of information, guidance and further sense of the structure of the data[9, 10, 13, 21]. The haptic instrument is used to reach in and probe the volumetric data, resulting in a force feedback representing the data at the tip of the probe.

The first developed and most straightforward implementations of such *volume haptics* make use of a direct mapping from vector properties in the data at the probed position to a force feedback (e.g. [9, 10]). Recent research, presented in [21], indicates that the information flow can be improved by using alternative metaphors that represent the structure of the data through *shapes* that are more naturally connected to the manner of interaction, as described for example by the *exploratory procedures* presented in [11]. The use of shape metaphors was shown to improve the identification of structures and features in the data.

Both the direct force mapping, in the form of force functions, and shape representations stimulate primarily the kinaesthetic sense of touch, dedicated for sensing macro structures and forces. We propose the use of such kinaesthetic metaphors as described above overlaid with tactile information about the data. This would allow for more information to be conveyed in such applications as multimodal scientific visualization. These two channels of information can be considered independent — vibrations with small amplitudes are detected by subcutaneous, tactile sensors, while relatively slow but large movements and forces are detected by proprioception, sensors in muscles and joints. In this paper we describe vibrotactile metaphors specially designed for representation of scientific data in combination with kinaesthetic feedback, show how these modalities can be combined and demonstrate, in a user study, the effectiveness of this combination.

The main contributions of this paper are

- the introduction of vibrotactile cues as complement to kinaesthetic metaphors in volume visualization
- the presentation of two vibrotactile metaphors for volume visualization
- a study on the effectiveness of using these as a complement to a shape metaphor

2 RELATED WORK

The methods described in the literature for *Direct Volume Haptics* (DVH) can be divided into two branches: force functions and constraint-based methods, discussed in subsections 2.1 and 2.2, respectively. Both these provide primarily kinaesthetic effects. Tactile modes of interaction are discussed at the end of this section, in particular vibrotactile means of information display in general (2.3) and for representing data and structures in 3D (2.4).

2.1 Force Function Methods

The most straightforward approach to DVH is the *force function*-based approach. Here the haptic feedback is expressed as a vector-valued function, $\vec{F}$, of the volumetric scalar or vector data at the position of interaction, the probe position, and the velocity of the probe

$$\vec{f} = \vec{F}(\Lambda, \vec{x}_{\text{probe}}, \vec{v}_{\text{probe}}) \tag{1}$$

where $\vec{f}$ is the force feedback, $\vec{x}_{\text{probe}}$ is the probe position and Λ is some property of the volumetric data. Various haptic effects from this approach have been used to produce palpable representations of the data and to guide the user to interesting areas. For example, pushing the haptic instrument in the direction of the local gradient in CT data,

$$\vec{f} = C\vec{\nabla}\Lambda(\vec{x}_{\text{probe}}) \tag{2}$$

where C is a positive or negative force scaling constant and Λ is the scalar data, has proved useful in certain exploratory tasks[9, 2, 20, 3]. The haptic instrument is then either pulled towards high density regions in the data or pushed towards low density data, respectively.

For vector data the most obvious approach is to use the vector as force feedback[9] although more advanced approaches have been proposed, for example in [10].

---

*karljohan.lundin.palmerius@liu.se

2.2 Constraint-based Methods

The constraint-based approach, first introduced in [17] and subsequently refined and applied in [8, 25, 16, 14, 15], was originally developed to provide a more intuitive representation of the volumetric data compared to force function-based methods. Here the local data at the probed position are used to define local passive constraints that represent those data at any position in the volume. By letting the constraint yield when subjected to a force exceeding some material-specific magnitude, occlusion is avoided and a continuous representation of the data is produced.

For example, the gradient vector in CT data has been used to generate a yielding constraint that represents surface-like features in the data[17, 8]. The feedback can be assigned tissue specific material properties, such as friction and the strength needed to penetrate the surface. The constraint-based approach has also been used to produce haptic feedback from vector data, by generating an anisotropic friction that produces a resistance when moving the probe perpendicular to the field[8, 16], or tube-like representations of vortices[16].

Common to these algorithms is the use of a proxy point, $\vec{x}_{\text{proxy}}$, an internal representation of the haptic probe. This proxy is fully controlled and moved by the haptic algorithms to render the desired effects. The force feedback, $vecf$, is then calculated using a virtual coupling, typically expressed as

$$\vec{f} = -k_s\left(\vec{x}_{\text{probe}} - \vec{x}_{\text{proxy}}\right) - k_d\left(\vec{v}_{\text{probe}} - \vec{v}_{\text{proxy}}\right) \qquad (3)$$

where k_s is a spring constant, k_d is a damping factor and $\vec{v}_{\text{probe}}$ and $\vec{v}_{\text{proxy}}$ are the probe and proxy velocity, respectively.

2.3 Vibrotactile Information Display

The use of vibrotactile feedback is a popular research topic and there is a large body of literature available with many applications. The actuators used to provide the feedback includes piezoelectric vibrators, speakers directed towards or located on the skin, and motors, either rotating with an unbalanced mass or directly producing the vibration. Since such actuators can be made very small they can be put almost anywhere from fingertip to somewhere else on the body, or in a held device or sewed into clothes. A review of techniques and applications for haptic data visualization by Panëels and Roberts in [22] includes a good overview of vibrotactile research.

In particular, the vibrotactile feedback has been used to some extent to convey large scale structural information. As an example Alles showed in [1] that vibrotactile stimuli on amputated patients can give phantom sensation providing a sense of kinaesthetics in prosthesis interaction. Cholewiak and McGrath studied in [6] the direction accuracy when using vibration for indication of directional whereabouts, for example to indicate danger. In a continuation[7] they also studied the use of combined visual and vibrotactile stimuli describing spatial patterns on display and on abdomen, respectively.

2.4 Vibrotactile Feedback from 3D Structures

Vibrotactile play-back has been used not only to present spatial cues and shapes, but also features and information distributed in 3D space. For example, Yang et al. describe in [26] a procedure where a tactile display distributed over the user's body is used to guide them to, as slave, follow a master. Lee et al. present in [12] a study where they used vibrations related to penetration depth, as the finger is moved through space around object to present structural information, such as a pictogram, to blind people. In yet another example, Van Esch-Bussemakers and Cremers describe in [24] a device that use vibrotactile actuators attached to PHANToM devices to playback tactile stimuli simulating different designs of feedback from virtual multimedia devices.

Vibrotactile cues have also been used to convey spatially distributed information in scientific visualization. Borst and Baiyya describe in [4] their work on using a vibrotactile array on one hand to provide an additional information channel during data exploration in 3D with the other hand. In a continuation of that project they presented in [5] a study on how position, direction and intensity profile on the vibrotactile array can communicate the spatially distributed information. Also, vibrations are applied by Menelas et al. in [18] as an alternative to viscosity for indicating closeness to critical points in flow visualization.

It should be noted that throughout this body of literature, no work has been found on combining vibrotactile and kinaesthetic metaphors for volume visualization.

3 VIBROTACTILE CUES FOR VISUALIZATION

The aim of this work is to overlay kinaesthetic metaphors of volumetric data with vibrotactile cues. The kinaesthetic feedback is capable of conveying structural information from volumetric data while the vibrotactile feedback can display multiple quantitative properties.

At a small scale the vibrotactile feedback is generated by a time-varying force or displacement of a skin contact. In this paper we assume that a 3D interaction device, such as a PHANToM device, is used to provide haptic feedback from volumetric data using a kinaesthetic algorithm for DVH. In this section we describe how the vibrotactile force is calculated to generate cues for scientific visualization. We propose two different vibrotactile metaphors: the roughness metaphor, an attempt at generating the sense of texture in 3D, and the transition cue metaphor, designed to generate an intuitive sense of transition between regions in the volume.

3.1 Roughness Metaphor

The roughness metaphor for volumetric data provides a 3D analogy to the roughness felt on surfaces. This can be seen as a free space variant of the roughness texture presented in [19]. It can be used in scientific visualization to reflect scalar volume data, or scalar properties of vector data such as the flow magnitude.

Roughness can be regarded a vibration caused by movements. To generate a vibration through a kinaesthetic instrument, a vibration in the force feedback is introduced,

$$\vec{f} = \vec{q}_{\text{vibr}} A \sin(\alpha(t)) \qquad (4)$$

where A is the amplitude and $\vec{q}_{\text{vibr}}$ defines the orientation of the vibration force vector. The angle, $\alpha(t)$ at time t, is defined as the accumulated angle over the simulation depending on the spatial frequency, $\frac{\omega}{2\pi}$, and the distance the haptic instrument has moved,

$$\alpha(t) = \alpha(t - \Delta t) + \omega\left|\vec{x}(t) - \vec{x}(t - \Delta t)\right| \qquad (5)$$

where $\vec{x}(t)$ is the position of the haptic instrument at time t. The data dependent roughness is then implemented by simply making ω a function of the data.

Since the roughness is rendered in free space we have no normal force that provides a natural modulation of the magnitude. This makes it necessary to add some automatic modulation, to allow for the convincing notion of roughness. For this we apply a modulation by velocity so that the amplitude becomes zero when the probe is stationary. The full amplitude should be applied already when a moderate speed is reached. Informal experiments indicate that a linear increase in amplitude works well and that it is suitable to apply full amplitude already at a velocity of a few cm/s.

Tappeiner et al. showed in [23] that the orientation vector, $\vec{q}_{\text{vibr}}$, can be used to convey a directional cue. It is not clear, however, how the direction of the vibration is perceived, that is whether kinaesthetic perception is involved and in that case if the direction cue from the vibration will interfere with the concurrent perception of a kinaesthetic data metaphors. The current aim is to separate proprioceptive and vibrotactile stimuli so that separate properties can

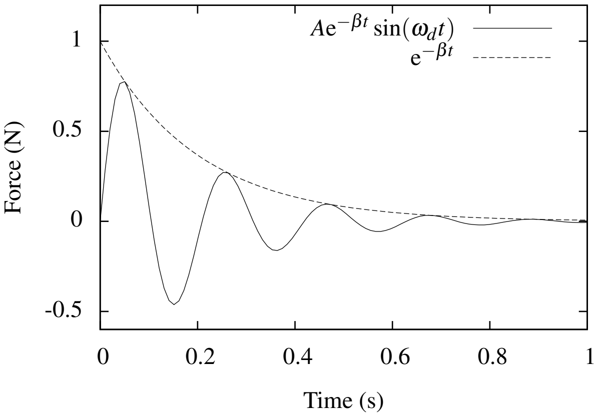

Figure 1: A graph illustrating the transient vibration added to produce the transition cue, here with $A = 1$, $\beta = 5$ and $\omega_d = 30$.

be represented by the two. Therefore, an arbitrary constant vector is used in the work presented here.

3.2 Transition Cue Metaphor

The transition cue metaphor provides a transient vibration to indicate for example the passing of an isosurface. This can be used to indicate any transition between regions, for example segmented tissues or areas of different vorticity.

A simple transient vibration suitable for this vibrotactile cue can be expressed as

$$\vec{f} = \vec{q}_{\text{vibr}} A e^{-\beta t} \sin(\omega_d t) \tag{6}$$

where A is the amplitude, ω_d is the damped angular frequency of the damped oscillator, β is the temporal absorption coefficient and $\vec{q}_{\text{vibr}}$ defines the orientation of the vibration, again set to an arbitrary constant vector. ω_d can be expressed as $\omega_d = \sqrt{\omega_0^2 - \beta^2}$, where ω_0 is the natural angular frequency and β the temporal absorption. A convenient way to express the the latter is in terms of the the relaxation time, τ, since $\beta = 1/\tau$.

This formula for transient vibrations has three parameters that can be used to indicate different transitions: amplitude, frequency and decay. In this paper, however, no study, test or opinion is provided on the effectiveness of such discrimination, that is whether or not different transitions can be identified using these properties of vibration. Only the use of a transient vibration for indicating a transition as such is suggested at this point and subsequently tested in the study below.

3.3 Combined Feedback

With a readily available algorithm for kinaesthetic feedback, for example from one of the references discussed in section 2.1 or 2.2, and the force equations described above, calculating the combined feedback is straightforward. We simply overlay the kinaesthetic feedback with vibrotactile by a vector sum of the individual force contributions. For example, with a proxy-based approach expressed by (3) together with the roughness metaphor expressed by (4) the feedback can be estimated as

$$\begin{aligned} \vec{f} \quad = \quad & -k_s \left(\vec{x}_{\text{probe}} - \vec{x}_{\text{proxy}}\right) \\ & -k_d \left(\vec{v}_{\text{probe}} - \vec{v}_{\text{proxy}}\right) \\ & +\vec{q}_{\text{vibr}} A \sin(\alpha(t)) \end{aligned} \tag{7}$$

The force added to produce the vibrotactile cues is fed back through the closed loop of the haptic system and care must be taken to ensure that this does not interfere with the rendering of kinaesthetic feedback. This can be ensured by simply keeping the amplitude, A, in (4) and (6) below the strength of the kinaesthetic features.

4 IMPLEMENTATION

The technique has been implemented by modifying the Volume Haptics Toolkit[13] (VHTK), an extension of H3D API from SenseGraphics. H3D API is a scene-graph system for the implementation of multimodal applications with three level programming: X3D for scene-graph definition, Python for scripting behaviour, and C++ for extending the functionality of the system. VHTK is a C++ extension that implements the kinaesthetic volume haptics based on haptic primitives.

All haptic metaphors in VHTK, or modes of feedback, extend a common base type (`VHTKHapticsModeNode`) that defines it as a scene-graph node, sets up all common functionalities and enlists the mode with the system core. We introduce the presented functionality by adding an abstract force shader base type (`VHTKHapticShader`). The term *shader* is here used in analogy with the programmable processing in common graphics hardware. Any node extending this type as well as the haptic mode type will become a force shader mode and can as such enlist as a force shader with the system core.

The core has been modified to call enlisted nodes with position and data information and collect the modulation force from each such node. This is done last in the procedure, after the kinaesthetic feedback has already been calculated. The force contribution from the vibrotactile nodes are then added to the kinaesthetic feedback before being sent to the haptic device.

5 EVALUATION

An evaluation has been performed to determine the effectiveness of this approach, to answer the question of whether or not a user of the system can make sense of the tactile cues while exploring the data using a kinaesthetic metaphor. It does not at this point study efficiency, comparisons or discrimination thresholds.

In this evaluation a combination of shape and vibrotactile metaphors is used. The objective is to find a combination of features represented by these metaphors, a straightforward but plausible task in scientific visualization.

5.1 Software and Settings

The implementation runs on an IW-19 from SenseGraphics equipped with a Desktop PHANToM from Sensable for haptic rendering and co-located stereo graphics, see Fig. 2. The graphics, however, was turned off during the experiment so that no cues about structure or position would be identifiable, such as a virtual stylus. Also, ear protectors were used to remove noise from the haptic device that would otherwise provide auditory cues.

Two data sets were used in this study: a kinaesthetic metaphor was used to explore the structure of vector data while the vibrotactile feedback represented a scalar data set. A synthetic data set with clear and unambiguous structure was designed as shown in figure 3. The vector data represent a straight flow along the x-axis to the left of the subject. At a randomized x-coordinate there is a bend resulting in a diagonal flow to the right of the subject. This bend is not instantaneous but extends over 20 mm.

The scalar data is designed so that each vibrotactile metaphor renders their specific feature at a randomized z-coordinate, forming a vertical plane in 3D. The roughness metaphor has a local reduction of frequency starting 20 mm in front of the plane, at its lowest at the plane and again increasing until 20 mm behind the plane. Thus, the frequency gradient for the roughness has a width of 40 mm. The transition cue metaphor provides the cue when the plane is passed

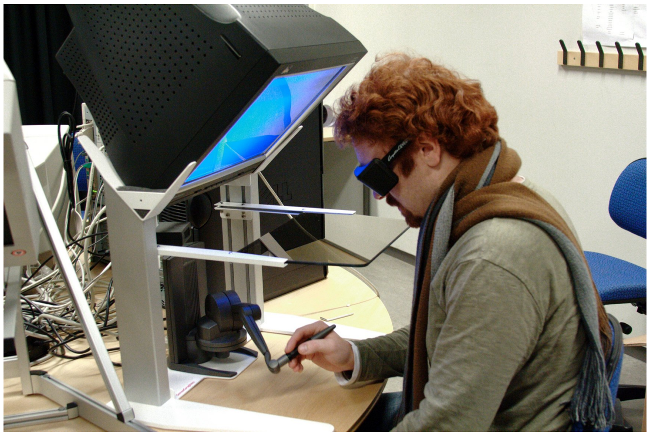

Figure 2: The haptic workstation used in the experiment, an IW-19 equipped with a Desktop PHANToM for haptic rendering and co-located stereo graphics.

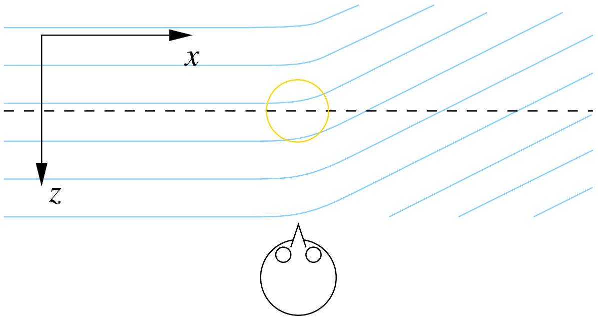

Figure 3: The test data seen from above. The vector data (solid lines) bends at a randomized x-coordinate. The scalar data has a feature at a randomized z-coordinate (dashed line). In the evaluation the subjects sought for the intersection (circle).

by the haptic probe in either direction. Velocity or orientation of transition has no effect on the feedback.

For the transition cue a frequency of 130 Hz was used with an amplitude of 0.3 N and a relaxation time of 100 ms. For the roughness simulation the low frequency at the plane and the high frequency regions elsewhere were given 2.5 and 0.4 mm periods, respectively. Assuming a typical exploration velocity of a few cm/s this corresponds to frequencies in the order of 10 and 100 Hz, respectively. The amplitude of the roughness force was set to 0.3 and 0.6 N, respectively, to adjust for differences in the hardware response at different frequencies.

5.2 Pretest Analysis

Since the two metaphors are specifically designed for tactile and kinaesthetic stimulation, respectively, they should in theory be distinguishable. There are, however, properties of the vibrotactile feedback indicate that the positional accuracy may be poor: no physical support or guidance is provided by the vibrotactile feedback. Also, while the transition cue metaphor provides a distinct feedback at the exact position of the feature, the roughness metaphor requires the subject to explicitly differentiate between different levels of roughness which may have an impact on the precision.

With this analysis as background we hypothesized as follows:

- The combination of features from the two data sets can be located with an accuracy significantly better than chance.
- The accuracy when using the roughness metaphor will be worse than for the transition cue metaphor.

5.3 Subjects

Eight subjects were used in this evaluation, all experienced with scientific visualization but with varying experience with haptics and haptic visualization. No monetary compensation was issued.

5.4 Procedure

The objective was to find a combination of features. With the transition cue metaphor the subjects were instructed to find where the isosurface in the scalar data intersects with the bend in the vector data and then mark this position with the haptic instrument. With the roughness metaphor they would find where the change in frequency intersects with the bend. The accuracy was measured as the distance between the subject's mark and the centre of the feature. Observe that since both features are defined in single orthogonal dimensions, the intersection is a line in 3D and thus the accuracy is measured in 2D.

Each subject marked the position of the feature intersection seven times for each metaphor. This gives us a total of 56 samples for each metaphor.

5.5 Results

All subjects understood the principles with only a short introduction and little practise, and were able to identify the combined features. The opinions of the subjects were recorded directly after exploring with each vibrotactile metaphor. We will here present both these opinions and the quantitative statistics.

5.5.1 Subjective Opinions

There was little agreement between the opinions of the subjects. One had trouble understanding the structure expressed through the kinaesthetic metaphor and another had trouble locating the position of the transition cue. Some of the subjects, however, expressed a lack of cues about the structure of the data presented through the vibrotactile metaphors. This was expected, as described in section 5.2. The subjects regarded the roughness metaphor as marginally better than the transition cue metaphor at conveying structure, since it has an extended distribution. This makes it possible to stroke along a structure and get a sensation of its shape and position. The transition cue metaphor on the other hand is only activated upon crossing the structure. There is no notion on the direction of the crossing, whether the probe was moved perpendicular to the structure or at an acute angle even almost parallel to the structure.

5.5.2 Quantitative Results

The 56 samples from the study form a sufficient basis for statistical analysis. The mean and standard deviation of the current location accuracy data were 14.1 and 9.7 mm, respectively, using the roughness metaphor and 7.6 and 7.0 mm, respectively, using the transition cue metaphor. Using confidence intervals on the respective means to estimate the accuracy on the general population, the accuracy is found to be, with a confidence level of 99%, in the range 10.7–17.6 mm using the roughness metaphor and 5.1–10.1 mm using the transition cue metaphor. These numbers are also illustrated in Fig. 4. By comparison, the accuracy by chance is in the current working space about 53 mm, and the size of the feature is 20×40 mm for the roughness metaphor and 20 mm for the transition cue metaphor, as described in section 5.4. This means that the average accuracy can be expected to be considerably better than chance.

The first hypothesis can be considered confirmed: the accuracy for both metaphors are better than chance. The second hypothesis, stating that the accuracy when using the roughness metaphor will be worse than for the transition cue metaphor, can also be considered confirmed since the respective confidence intervals do not overlap.

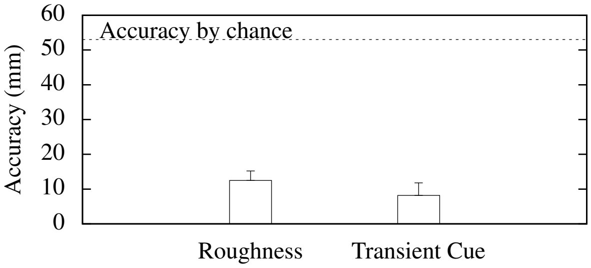

Figure 4: The accuracies (bars) during the experiment and their one-sided 99% confidence interval (whiskers). The accuracy by chance is also presented as a comparison.

6 CONCLUSIONS

The study presented in this paper shows that spatial vibrotactile cues can be used together with kinaesthetic feedback as representations of volumetric data, that this combination is effective and that a combination of features from the two metaphors can be identified and located in space. The spatial accuracy was shown to be within the centimetre range, even better than the order of the size of the target. It is also shows that the design of the vibrotactile metaphors has a strong impact on the spatial precision, as has already been shown for kinaesthetic feedback in [21].

In the presented work only one type of shape metaphor has been used. It is, however, expected that also other kinaesthetic metaphors, such as force functions and other shape metaphors, will be equally combinable with the vibrotactile cues.

ACKNOWLEDGEMENT

This work was supported by the Swedish Research Council in the Linnaeus Centre CADICS, and by Swedish Foundation for Strategic Research in the centre MOVIII.

REFERENCES

[1] D. S. Alles. Information transmission by phantom sensations. *IEEE Transactions on Man-Machine Systems*, MMS-11(1):85–91, March 1970.
[2] R. S. Avila and L. M. Sobierajski. A haptic interaction method for volume visualization. In *Proceedings of IEEE Visualization*, pages 197–204, October 1996.
[3] D. Bartz and Özlem Gürvit. Haptic navigation in volumetric datasets. In *Proceedings of PHANToM User Research Symposium*, 2000.
[4] C. Borst and V. Baiyya. Enhancing VR-based visualization with a 2D vibrotactile array. In *Proceedings of ACM Symposium on Virtual Reality Software and Technology*, 2007.
[5] C. W. Borst and V. B. Baiyya. A 2D haptic glyph method for tactile arrays: Design and evaluation. In *Proceedings of the IEEE World Haptics Conference*, 2009.
[6] R. W. Cholewiak, C. Brill, and A. Schwab. Vibrotactile localization on the abdomen; effects of place and space. *Perception & Psychophysics*, 66(6):970–987, 2004.
[7] R. W. Cholewiak and C. McGrath. Vibrotactile targeting in multimodal systems: Accuracy and interaction. In *Proceedings of the Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, 2006.
[8] M. Ikits, J. D. Brederson, C. D. Hansen, and C. R. Johnson. A constraint-based technique for haptic volume exploration. In *Proceedings of IEEE Visualization*, pages 263–269, 2003.
[9] H. Iwata and H. Noma. Volume haptization. In *Proceedings of IEEE 1993 Symposium on Research Frontiers in Virtual Reality*, pages 16–23, October 1993.
[10] D. A. Lawrence, L. Y. Pao, C. D. Lee, and R. Y. Novoselov. Synergistic visual/haptic rendering modes for scientific visualization. *IEEE Computer Graphics and Applications*, 24(6):22–30, 2004.
[11] S. J. Lederman and R. L. Klatzky. Hand movements: A window into haptic object recognition. *Cognitive Psychology*, 19(3):342–368, July 1987.
[12] B.-C. Lee, H. Park, J. Lee, and J. Ryu. Tactile visualization with mobile ar on a handheld device. *Lecture Notes in Computer Science*, 4813:11–21, 2007.
[13] K. Lundin, M. Cooper, A. Persson, D. Evestedt, and A. Ynnerman. Enabling design and interactive selection of haptic modes. *Virtual Reality*, 11(1):1–13, March 2006. DOI: 10.1007/s10055-006-0033-7.
[14] K. Lundin, B. Gudmundsson, and A. Ynnerman. General proxy-based haptics for volume visualization. In *Proceedings of the IEEE World Haptics Conference*, pages 557–560, Pisa, Italy, March 2005. IEEE.
[15] K. Lundin, C. Lundström, M. Cooper, and A. Ynnerman. Enabling haptic interaction with volumetric mri data through knowledge-based tissue separation. In *Proceedings of the International Workshop on Volume Graphics*, pages 75–78, 2006.
[16] K. Lundin, M. Sillen, M. Cooper, and A. Ynnerman. Haptic visualization of computational fluid dynamics data using reactive forces. In *Proceedings of the Conference on Visualization and Data Analysis, part of IS&T/SPIE Symposium on Electronic Imaging 2005*, San Jose, CA USA, January 2005.
[17] K. Lundin, A. Ynnerman, and B. Gudmundsson. Proxy-based haptic feedback from volumetric density data. In *Proceedings of the Eurohaptic Conference*, pages 104–109. University of Edinburgh, United Kingdom, 2002.
[18] B. Menelas, M. Ammi, L. Pastur, and P. Bourdot. Haptical exploration of an unsteady flow. In *Proceedings of the IEEE World Haptics Conference*, 2009.
[19] M. Minsky and S. Lederman. Simulated haptic textures: Roughness. In *Proceedings of the ASME Dynamic Systems and Control Division*, 1996.
[20] A. Mor, S. Gibson, and J. Samosky. Interacting with 3-dimensional medical data: Haptic feedback for surgical simulation. In *Proceedings of Phantom User Group Workshop*, 1996.
[21] K. L. Palmerius and C. Forsell. The impact of feedback design in haptic volume visualization. In *Proceedings of the IEEE World Haptics Conference*, pages 154–159, Salt Lake City, USA, March 2009. IEEE.
[22] S. Panëels and J. C. Roberts. Review of designs for haptic data visualization. IEEE Transactions on Haptics (PrePrint), September 2009.
[23] H. Tappeiner, R. Klatzky, B. Unger, and R. Hollis. Good vibrations: Asymmetric vibrations for directional haptic cues. In *Proceedings of the IEEE World Haptics Conference*, Salt Lake City, USA, March 2009. IEEE.
[24] M. P. van Esch-Bussemakers and A. H. M. Cremers. User walkthrough of multimodal access to multidimensional databases. In *Proceedings of the International Conference on Multimodal Interfaces*, 2004.
[25] E. Vidholm, X. Tizon, I. Nyström, and E. Bengtsson. Haptic guided seeding of MRA images for semi-automatic segmentation. In *Proceedings of IEEE International Symposium on Biomedical Imaging*, 2004.
[26] U. Yang, Y. Jang, and G. J. Kim. Designing a vibro-tactile war for “close range” interaction for vr-based motion training. In *Proceedings of International Conference on Artificial Reality and Telexistence*, 2002.