Adding Tangential Forces in Lateral Exploration of Stiffness Maps

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Abstract. We believe that the lateral exploration of surfaces with varying stiffness, *stiffness maps*, using computer generated haptics is an underestimated and important procedure with impact in many application areas. Feeling the change of stiffness while sweeping the haptic probe over a surface can potentially give an understanding of the spatial distribution of this stiffness, however current algorithms lack tangential cues of stiffness changes. This introduces energy sources and sinks that potentially affects the stability of the system, apart from being physically incorrect and thus unrealistic. We discuss the forces and effects involved in the exploration of stiffness maps and propose an energy-based algorithm for tangential forces that augments the feedback from the map, in particular during lateral exploration. The algorithm is based on basic physical principles and has the potential to increase both realism and stability. A user study was conducted to analyze the effect of this algorithm on stiffness perception.

Keywords: stiffness map, kinaesthetics, lateral forces, energy

1 Introduction

The use of point-based, haptic interaction devices is a popular method of introducing touch in computer environment. These devices typically provide primarily kinaesthetic feedback. The application area considered in this paper is the haptic rendering of surfaces with varying stiffness, *stiffness maps*, for example for the purpose of medical palpation to identify sub surface structures or for data exploration. The objective of palpation is typically to locate or assess the spatial distribution of features. Our own interest in this is for the realistic rendering of skin with the inclusion of bone and vessels for the probing for needle insertion. Other interesting applications are the exploration of CT or MRI as presented by Yano et al. in [15] and the exploration of nano surfaces captured through scanning probe microscope as presented by Choi et al. in [5].

The exploratory procedures presented by Lederman and Klatzky in [10] indicate that the primary means of exploring stiffness is by applying *pressure* and that *lateral motion* is used primarily to explore texture. Choi et al.[5], however, provide an analysis of a topographic interpretation of stiffness maps during lateral motion that indicates an important connection between this exploratory procedure and the interpretation of stiffness. The different forces available in the exploration of stiffness maps and their implementation in computer generated feedback may have an impact on this interpretation. This paper provides an attempt at analyzing the forces involved.

We believe that lateral exploration of stiffness maps is an underestimated and important procedure with impact in many application areas. Feeling the change of stiffness while sweeping the haptic probe over a surface can potentially give an understanding of the spatial distribution of this stiffness. We propose an energy-based algorithm for tangential forces from stiffness maps that augments the feedback from stiffness maps, in particular during lateral exploration. The algorithm is based on physical principles and has the potential to increase both realism and stability by removing unnatural energy sources and sinks in the basic stiffness rendering.

The contributions of this paper are:

- an analysis of the haptic exploration of stiffness maps
- the proposal of an energy-based algorithm producing tangential forces from stiffness maps for increased realism and stability
- a study on the effect of such forces on the just noticeable stiffness difference (JND) during lateral exploration of stiffness maps

2 Background and Related Work

Though second to surgery simulation, the use of haptic techniques to simulate the procedure of palpation is quite common. Research in this area, however, largely overlaps with the research on surgery simulators, in that they are often based on soft body deformation models. There are also situations where the full dynamic simulation of soft tissues is not necessary for the conveying of plausible haptic sensation. In such situations off-the-shelf algorithms for surface rendering can be used for the general sensation of the palpated skin surface, overlayed with feedback specific to the current palpation simulation. An example of this is the palpation of femoral pulse by Coles et al.[6]. There the surface feedback is overlayed by force feedback simulating the pulse, as well as tactile feedback through piezoelectric elements on the finger tips.

The spring stiffness constant used in the typical surface rendering algorithm can be interpreted as reflecting the hardness of the rendered surface. By varying this constant over the simulated surface, a stiffness map, the sensation of varying hardness is achieved. Yano et al. use this technique to perceptualize the cross section of CT data or MRI[15]. The same year, Choi et al. presented a similar effort, however on scanning probe microscopy (SPM) data[5].

Choi et al. also showed that the topography of a surface may be misinterpreted if both the height of the surface and its stiffness varies spatially. In a continuing effort on this topic they compensate for this effect by adding a dynamic bias to the surface height so that the normal directed force is always the same during a purely lateral motion[2, 4]. They have also experimented with using force shading to render the slant of the varying surface height[3].

3 Stiffness Exploration

Two approaches to exploring stiffness of surfaces are mainly considered in the literature. Applying pressure is described by the exploratory procedures presented by Lederman and Klatzky in [10] as the primary means of acquiring knowledge about object hardness. An alternative is the lateral exploration that may be important to assess the spatial distribution of any property, be it shape or temperature or, as in our case, stiffness. Here follows a discussion on the forces and effects involved in these procedures with a motivation for extending the typical rendering algorithm.

3.1 Surface Feedback

There are many variations of algorithms for producing haptic feedback from geometrical surfaces. The algorithms for point-based, kinaesthetic, impedance control haptic feedback, considered here can be considered to have evolved through three steps. First the *penalty method* was used[12, 14]. In that approach the penetration of objects is penalized by a force feedback. The larger the penetration, the greater the force. The penalty method has been largely replaced by the *god-object method*[16, 7] which removes the worst haptic artifacts associated with the penalty method. These appear primarily with thin objects and around sharp edges. Finally the *proxy-based approach*[13] was introduced by Ruspini et al. It works better with complex and dynamic polygonal objects and has therefore replaced the god-object method in some systems.

All these algorithms follow the same basic principle: the haptic probe penetrates the surface and a spring simulation, or equivalent in the form of for example a PI regulator, provides feedback that pushes the instrument towards the surface. The most elementary implementation of this is the penalty approach, which we will use as example in this paper. Here friction is ignored and the normal directed force feedback, $\mathbf{F}_\mathrm{N}$, is calculated from the pure penetration of the surface,

$$\mathbf{F}_\mathrm{N} = -k_\mathrm{s}\left(\mathbf{x}_\mathrm{probe} - \mathbf{x}_\mathrm{surface}\right) \tag{1}$$

where k_s is the surface stiffness, $\mathbf{x}_\mathrm{probe}$ is the position of the haptic probe and $\mathbf{x}_\mathrm{surface}$ is the probe's projection onto the surface, representing the optimal virtual position of the haptic probe, see Fig. 1.

When this algorithm is used to render a stiffness map the surface stiffness property is defined as a function of the probe's projection on the surface,

$$\mathbf{F}_\mathrm{N} = -k_\mathrm{s}(\mathbf{x}_\mathrm{surface})\left(\mathbf{x}_\mathrm{probe} - \mathbf{x}_\mathrm{surface}\right) \tag{2}$$

This principle is similar in all algorithms mentioned above.

3.2 Pressure Procedure

During the pressure procedure the haptic probe is primarily moved in the direction of the normal of the surface. The real world equivalent would be the

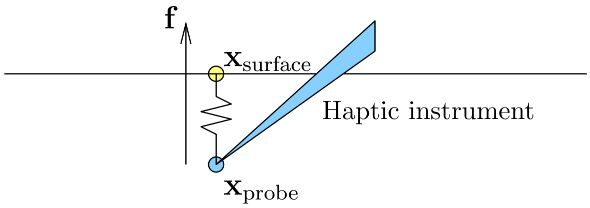

Fig. 1. The principle of the penalty method: the penetration of the surface is penalized with an increasing opposing force according to Hooke's law.

compression of a deformable object. The stiffness of the object is perceived as a force/displacement relationship during this exploration, primarily the change in force caused by change in compression. An alternative model is presented by Lawrence et al. in [9]. Their *rate-hardness* model identifies surface hardness as the initial rate of force change (N/s) relative the penetration velocity (m/s).

Regardless of model, the main cue is normal directed force change due to normal direction motion. In interaction and exploration with distribution stiffness, as with the topical stiffness map, the user is forced to focus on normal directed motion. Thus, the exploration of stiffness *distribution* will be performed by sampling at discrete points through pressure. This requires the user to explicitly remember multiple discrete data points and mentally merge these into a continuous visualization of the stiffness distribution.

3.3 Lateral Exploration

An alternative exploration of a stiffness map would be using lateral motion. With this approach the user can perceive the change of stiffness over the spatial region of the chosen path of exploration. The change of procedure, however, is bound to change the perception of the surface stiffness, as indicated by Lederman and Klatzky's exploratory procedures ([10]).

Normal Directed Forces There will be normal directed forces regardless of the exploratory procedure used. When the primary motion is lateral over the surface, however, the change in penetration depth is small compared to the general motion. Thus the highly dynamic and low resolution sense of proprioception may have problems associating the normal directed change of force with this change in penetration depth. The research of Choi et al.[5] indicates that the perception of stiffness as a force/displacement relationship diminishes during lateral exploration and that other cues become more important. They showed that the probing hand is subconsciously moved in a way so that the applied normal force is held constant during lateral exploration. In such situations the primary perception is the change of penetration depth, which was shown to be interpreted as changes in the topography of the surface. We have conducted an informal experiment that confirm this sensation and it is at the same time consistent with

Lederman and Klatzky's exploratory procedure called *contour following*. There is no reason to suspect that a user would be incapable of interpreting such sense of changes in surface height as changes in stiffness, however in the interaction of both changing topography and stiffness there is little chance of telling these cues apart.

In their work Choi et al. change the height of the surface in the haptic algorithm to compensate for the perceived change in height caused by the change in stiffness. This allowed for a better interpretation of the topography, however will at the same time remove a cue of stiffness change. An informal experiment confirms that a user has to resort to the pressure procedure to be able to feel changes in the stiffness map when height compensation is activated. This is of course a trade-off strongly dependent on the application at hand.

Tangential Forces Current implementations of stiffness maps do not provide any tangential forces as response to changes in the stiffness over the surface, however such forces do exist in reality. On a frictionless surface a finger pushing into the surface will be moved by tangential forces into a local stiffness minimum. This is shown through physical equations in the following section and to allow for effective exploration of stiffness with also lateral motion the system should provide these tangential cues of stiffness variation.

4 Energy-based Tangential Force

Without tangential forces the exploration of a surface with varying stiffness will introduce energy sources and sinks without physical counterparts. The algorithm for a tangential feedback force presented in this paper is based on removing this energy, leading to conservation of energy in the system.

Compressing a surface and then moving the probe laterally from one area into another with higher stiffness will store potential energy. The spring-based potential energy, $E_p(\mathbf{x})$, for the feedback at a point on the surface, $\mathbf{x}$, is expressed as

$$E_p(\mathbf{x}) = \int_0^D k_\mathrm{s}(\mathbf{x}) r \; \mathrm{d}r = k_\mathrm{s}(\mathbf{x}) D^2/2 \tag{3}$$

where k_s is the stiffness map, a function in $\mathbb{R}^2$ over the surface, and D is the current penetration depth, $D = |\mathbf{x}_\mathrm{probe} - \mathbf{x}_\mathrm{surface}|$. Changing stiffness over lateral motion results in change of potential energy. If this motion is allowed without tangential force, the added energy will not correspond to dissipated energy anywhere else violating the conservation of energy in the system. The energy flow is equal to the force integrated along the path so it follows, by spatial derivation, that

$$\nabla E(\mathbf{x}) = \mathbf{F}(\mathbf{x}) \tag{4}$$

where $\mathbf{F}$ is the force corresponding to the change in energy. Combining Eqn. 4 and 3, while changing the sign to make it *remove* energy, we get

$$\mathbf{F}_\mathrm{T}(\mathbf{x}) = -\nabla k_\mathrm{s}(\mathbf{x}) D^2/2 \tag{5}$$

where $\mathbf{F}_\mathrm{T}$ is the tangential force required to compensate for the energy flow due to the surface compression during lateral exploration. The del operator is operating in 2D, since k_s is a function defined in 2D, and $\mathbf{F}_\mathrm{T}$ will therefore always be tangential to the surface.

Calculating the final force feedback is straightforward. We estimate the gradient of the stiffness map using Gaussian weighted central difference. Then, for the penalty-based approach used here, the energy conserving tangential force, $\mathbf{F}_\mathrm{T}$, is simply combined by vector addition with the normal directed force. For god-object or proxy-based approaches, the calculated force is instead used to modulate the proxy motion over the surface, together with other modulating effects such as friction or bump maps. This approach should be fully compatible with varying geometrical structures as well as force shading[13].

This algorithm has several qualities: it is based on simple physical facts and therefore more realistic by definition, it is very straightforward in its mathematical and algorithmic appearance and thus also easy to implement. With this algorithm in place moving the haptic probe laterally with constant penetration depth from a soft area into a stiffer area, for example, gives a resistance providing the sense of loading a spring. This energy is then released and absorbed by the user when moving the haptic probe to a level with the original stiffness.

5 User Study

The added tangential force makes, by physical definition, the feedback more realistic. In the context of lateral exploration for the purpose of surface examination, however, we wish to analyze how the perception of the stiffness variation is affected. This study aims at testing if the just-noticeable-difference quality (JND) is affected by the tangential force with everything else left identical. A result where the increased realism comes with no or little deterioration of perception would be considered a good result, an improvement would be optimal and a significant deterioration would be a strong contraindication for the use of this algorithm for most applications.

5.1 Software and Settings

The presented algorithm was implemented in a very simplistic computer program allowing only a flat surface, no friction and an image-based stiffness map. The system was implemented in H3D API but without using their surface rendering capabilities. The system runs on a haptic workstation equipped with a Desktop PHANToM device from Sensable and a stereoscopic CRT monitor showing visual rendering for navigation. The graphics provide no cues of stiffness during the experiment.

Method The study follows a within-subject design with one independent variable having two levels: normal directed force only (N) and normal directed and tangential forces (N+T). We apply the psycho-physical staircase procedure[11], which is designed to gradually advance towards a stimuli level at which the subject can, to a certain degree, identify the strongest stimuli among a certain amount of choices. This study apply four alternatives forced choice (4-AFC) with a one up two down staircase, with termination after six reversals and using the mean of the last three reversals as result level.

We apply an adaptive approach[8] to control the step size in the staircase. This improves the convergence while maintaining high precision in the final result. The experiment uses an initial step size of 5 percentage points and ends up with a step size of 1 percentage point before the last reversals.

Procedure The subjects were confronted with a square surface with five regions, see Fig. 2. Four grey corner squares represent the choices. Three of these regions have the base stimuli level and one is harder than the other. A base level of 200 N/m was chosen since this provides considerable feedback at moderate surface penetration while being well within the stability range for the haptic device even for a high stimuli level. The white centre cross is 20% softer than the base level and functions as an intermediate blank to remove direct comparison between the patches.

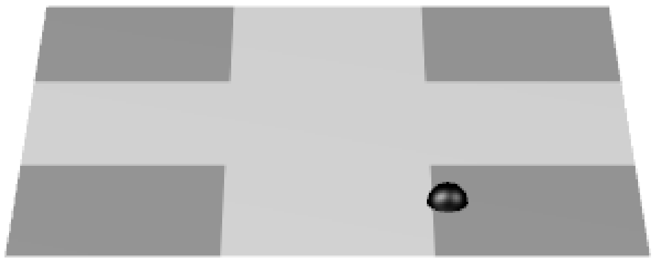

Fig. 2. This image shows the important part of the screen during the experiment. Three of the four grey squares are of base stiffness and a randomly selected one is stiffer. The white cross is softer and removes direction comparison between patches. The small sphere is the graphical representation of the haptic probe.

The subjects explored the surface laterally with no explicit normal motion which was controlled by a supervisor. They were not introduced to the difference between the conditions, knowledge that one is more physically correct could add a bias, and the order of appearance was balanced. The objective was to find the harder patch. Its correct location was randomized and the selection was done by pressing a button on the haptic instrument on the chosen patch.

As an initial search for an entry level the task was first very simple, the harder surface being 100% stiffer than base stiffness. This was then quick lowered by halving the difference for every second right answer until two consecutive wrong answers were given. The mean of the last successful and the failed difference was calculated and the staircase was initialized at this level, following with the adaptive approach from there. This approach proved very effective with very few subjects deviating more than one or two initial step sizes from their starting points. The test took approximately 20 minutes.

Participants Ten subjects, aged 25–34, took part in the evaluation. They have all technical background but varying experience of computer simulated haptics. No monetary compensation was issued.

5.2 Pre-test Analysis and Hypothesis

Preliminary tests showed very little difference between the conditions. Possibly the N condition could perform somewhat better than the N+T condition. This suggests that primarily the sense of height difference is used to determine the stiffness and that the tangential forces may obscure this sensation. A hypothesis that the N condition performs better than the N+T condition is suggested, which would then support this theory. Since the preliminary tests are inconclusive to whether this is a good hypothesis we also suggest the contradictory hypothesis, that the N+T condition performs better than the N condition.

We prepared to test these hypotheses for statistical significance using the dependent t-test. This test takes into account the individual differences and is therefore useful when the performance varies a lot between subjects. Also, because of important shortcomings in significance tests[1], we choose to show prediction intervals of the result as well.

5.3 Results

The mean of the four last reversals was taken for each subject. A simple statistical analysis of the basic properties of the resulting JND data over all subjects yields a mean of 16.3% and 8.4% for the N and N+T conditions, respectively, and a standard deviation of 22.1% and 4.2%, respectively. Before further statistical analysis can be conducted the logarithm is applied to the data to remove the skew inherent to the nature of the data and transform it into a Normal distribution. The 95% confidence intervals of the mean JND for the individual conditions are 5.1%–19.5% for the N condition and 5.1%–10.8% for the N+T condition.

A dependent t-test shows that the difference of mean JND between the two conditions is not statistically significant with $p = 0.22$. This is with a two-tailed test since both hypotheses are tested simultaneously. The two one-tailed tests, however, are not significant either. Thus, both stated hypotheses are rejected: the difference between the conditions is too likely to be the result of noise to be considered statistically assured.

A confidence interval over the relationship will, since we applied the logarithm, be expressed as the quotient of the JND means, $\frac{\mathrm{N+T}}{\mathrm{N}}$. With 95% confidence the quotient between the means lies within the range 0.45–1.23. This shows why there is no statistical significance of the difference between the conditions, since 1.0 is included in the range. Interesting, however, is that the upper limit is not very high. With a one-sided confidence limit we find out that with 95% confidence the JND for condition N+T is not more than 11.8% worse than that of N.

6 Discussion and Conclusions

The mean JND for lateral exploration with both normal directed and tangential forces, using the energy-based algorithm, was shown to be at most 11.8% worse than that of exploration with normal directed forces alone, with a confidence level of 95%. Observe that this is percentage of JND, *not* percentage points. This is a side effect of using the logarithm for transforming the data with the logarithm. As an illustrative but purely hypothetical example, if the mean JND for the N condition happens to be 16.3%, then the JND for the N+T condition is *at most* 20.0%, a mere 3.7 percentage points difference at that level, with 95% confidence.

These results indicate that the increased realism provided by the presented algorithm comes with no or little deterioration of the JND between stiffness levels during lateral exploration of a surface. While the optimal outcome was not shown in this study, that the algorithm provides improved perception of JND, this is still a positive result showing that this algorithm can be used to increase the realism and stability without fear of a large deterioration of the feedback quality. The lack of improvement can possibly be explained by the interpretation of stiffness change as topographic change. Haptic shape cues are strong and since we used no height compensation[2] their effect may overshadow any improvement caused by the lateral forces.

We have presented a physics-based, elementary and easy to implement algorithm introducing tangential feedback during the exploration of stiffness maps, and discussed how this is of special importance during lateral exploration. This algorithm is shown to remove energy sources and sinks in stiffness maps which is anticipated to improve both realism and stability. We have also studied whether the increased realism comes with a penalty or improvement on the JND during lateral exploration. The results indicate that the effect, if any, is small and that the conclusive characterization of it would require a larger study. This study, however, shows that the algorithm at most worsen the perception with 11.8% with a confidence level of 95%, possibly even improving it.

Adding this tangential cue for stiffness change over lateral exploration may also remove the importance of the height cues described in section 3.3. Testing simultaneous topographic and stiffness exploration with height compensation and energy-based tangential forces is an interesting future project on this topic.

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