The Role of Contact Area Spread Rate in Haptic Discrimination of Softness

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Abstract

Many applications in teleoperation and virtual reality call for the implementation of effective means of displaying to the human operator information on the softness and other mechanical properties of objects being touched. The ability of humans to detect softness of different objects by tactual exploration is intimately related to both kinesthetic and cutaneous perception, and haptic displays should be designed so as to address such multimodal perceptual channel. Unfortunately, accurate detection and replication of cutaneous information in all its details appears to be a formidable task for current technology, causing most of today's haptic displays to merely address the kinesthetic part of haptic information. In this paper we investigate the possibility of surrogating detailed tactile information for softness discrimination, with information on the rate of spread of the contact area between the finger and the specimen. Devices for implementing this new perceptual channel are described, and some preliminary psychophysical test results are reported, validating the effectiveness and practicality of the proposed approach.

1   Introduction

When exploring such mechanical properties of an object as stiffness, damping, hysteresis, humans use their fingers to squeeze or indent the surfaces, and gather data from many sensorial receptors in the hand. The variety of sensors used in such tasks can be divided in two broad functional classes, or sensory channels, namely kinesthetic and cutaneous (or tactile) sensors (see e.g. [8]). Kinesthetic information refers to geometric, kinetic and force data of the limbs, such as position and velocity of joints, actuation forces, etc., which is mainly mediated by sensory receptors in the muscles, articular capsulae, and tendons. Cutanueous information refers to pressure and indentation distributions, both in space (on the skin) and in time, and is mediated by mechanoreceptors innervating the derma and epidermis of the fingerpads. Other sensory information (such as thermal) may concur to exploration by touch.

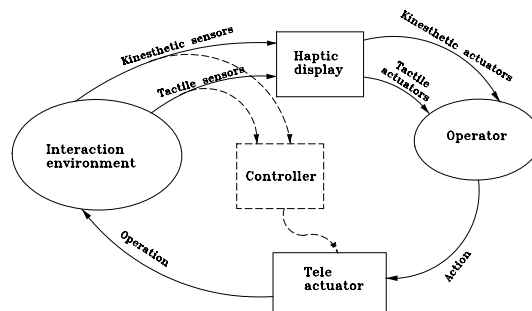Information synergistically conveyed by the kinesthetic and tactile channels, and elicited by the cen-

Figure 1: A schematic representation of a Remote Haptic System)

tral nervous systems, forms the object of "haptic", or touch–related, sciences and technologies [11].

In this paper, we focus our attention on a particular haptic task, that of discriminating different objects by their rheological properties [1], and on the realization of a system for allowing an operator to remotely perform such operation, i.e. a Remote Haptic System. An RHS is comprised in general of a telemanipulator, allowing the human operator to perform exploratory actions on the remote specimen, and an haptic communication channel, conveying back information to the operator (see fig.1). Communication of haptic information involves both sensing performed at the remote end of the loop, and display on the operator side. In full generality, two channels should be available to sense and display kinesthetic and tactile information.

To illustrate a particular embodiment of the RHS description of fig.1, let us refer to the case of a system for remote palpation of tissues in minimally invasive laparoscopy. This application is one of the most promising for the new haptic technologies, and has been considered by several authors ([4], [7], [3], [1]). In this case, the telemanipulator subsystem is quite simply

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[1]Rheology of materials studies their deformations and flows, and rheological properties include common notions of softness/compliance, damping, plasticity, hysteresis

embodied by the standard laparoscopic tool handled by the surgeon, which can be used to palpate a given specimen in order to recognize the characteristics and nature of its tissue. Kinesthetic data, which are not directly available to the surgeon because of the forceps mechanism ([15]), could be sensed by force and position transductors near the laparoscopic forceps, such as those based on strain–gauges and LED/PSD pairs described in [1]. A display of kinesthetic information can be realized by suitably controlling a robotic mechanism, such as for instance [12] or [14], to behave according to a given mechanical impedance model. On the other hand, tactile sensing should be implemented right on the tips of the forceps jaws in the form of an array of distributed pressure–sensitive elements; and tactile actuation could be realized by an array of mechanical indenters, acting on the operator fingerpad.

At the present state of the art and technology, the parts of the haptic system of fig.1 that are most difficult to implement are definitely those referring to cutaneous tactile information. Although there have been prototypal implementations of such sensory and displaying systems, as e.g. those described by [5] and [7], the need for miniaturization, simplicity, economy, and ruggedness of many applications, including the surgical one above described, make the display of tactile information indeed a formidable task. Because of these technological difficulties, most present–day RHS only include a kinesthetic information channel. Unfortunately, several psychophysical experiments have clearly demonstrated that loss of the tactile channel reduces human capability of haptic discrimination dramatically (see [16] and [10]).

In this paper, we illustrate a psychophysical conjecture concerning a much simplified form of tactile information, which we call the Contact Area Spread Rate (CASR) paradigm. Devices for sensing and displaying the CASR are presented, and experiments are reported that validate, albeit preliminarly, the CASR paradigm.

2 The CASR conjecture.

Observation of haptic exploration of objects in humans, such as described in the psychophysical literature ([16], [10]) and by everyday experience, definitely shows that kinesthesia alone can not supply sufficient information for most haptic tasks, and that tactile information is instrumental. However, tactile information in humans is extremely rich in content and purposes, and it might not be the case that all its richness is actually necessary to discriminate softness of different materials, which is our ultimate goal in this research. As an example, it is easily verified that, up to some indesirable "haptic illusions", softness discrimination is not affected by the finger touching the surface of a specimen at different orientations; nor is it very sensitive to the location of the contact area on the finger surface. These observations lead to consider haptic discrimination of softness as fundamentally invariant with translations and rotations of the contact area.

One may go further on this line of reasoning, and find other aspects of fine cutaneous imaging available to humans, to be scarcely relevant to haptic discrimination of softness. For instance, the actual *shape* of the contact zone between the finger and the object does not seem to be by far as relevant as the *area* of the zone itself. More precisely, we conjecture that a large part of haptic information necessary to discrimate softness of objects by touch is contained in the law that relates overall contact force to the area of contact, or in other terms in the rate by which the contact area spreads over the finger surface as the finger is pressed on the object. We call this relationship the Contact Area Spread Rate (CASR).

As one further motivation for our conjecture, consider standard Hertz modeling of contact between elastic bodies [9]. Although this theory applies to homogeneous, isotropic bodies of size much larger than that of the contact area, and this is not usually the case in many RHS applications (such as e.g. in laparoscopic surgery), still it is interesting to verify that our conjecture makes sense in this case.

In the hertzian contact between two spheres, the contact area has circular shape of radius a, and the equation describing the relative displacement of corresponding points of objects within the contact area is

$$\overline{u}_{z1} + \overline{u}_{z2} = \delta - \frac{r^2}{2R} \tag{1}$$

where $\delta = \delta_1 + \delta_2$ is the relative displacement of two bodies, $\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$ is the relative curvature, r is the radial distance from the center of contact ($r \leq a$) (see Figure 2).
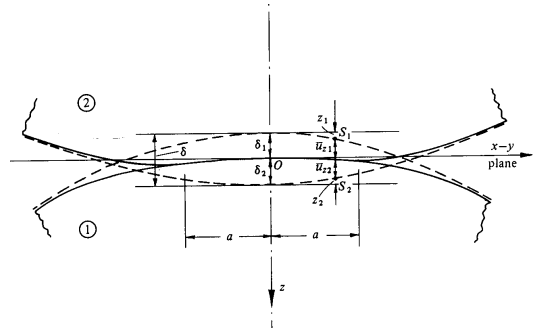

Figure 2: Hertzian contact between two bodies.

The pressure distribution law proposed by Hertz is given by

$$p(r) = p_0 \left[1 - \left(\frac{r}{a} \right)^2 \right]^{\frac{1}{2}}, \tag{2}$$

and the displacements within the loaded area are

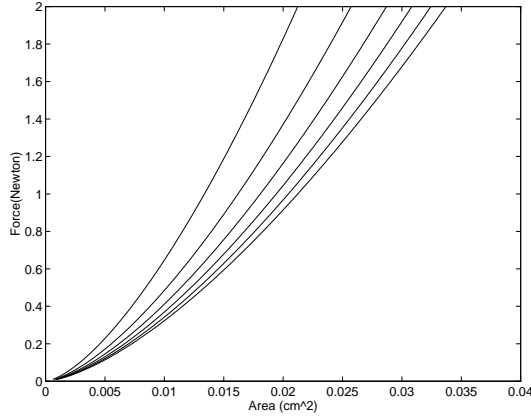$$\overline{u}_{zi} = \frac{1 - \nu_i^2}{E_i} \frac{\pi p_0}{4a} (2a^2 - r^2), \quad r \leq a. \tag{3}$$

Figure 3: Contact force/area curves for the hertzian model of contact between a spherical finger with $E_1 = 0.25 MpA, \nu_1 = 0.5, R_1 = 5mm$, and six specimens with $\nu_2 = 0.5, R_2 = 10mm$, and E_2 ranging linearly between $E_1/2$ and $2E_1$.
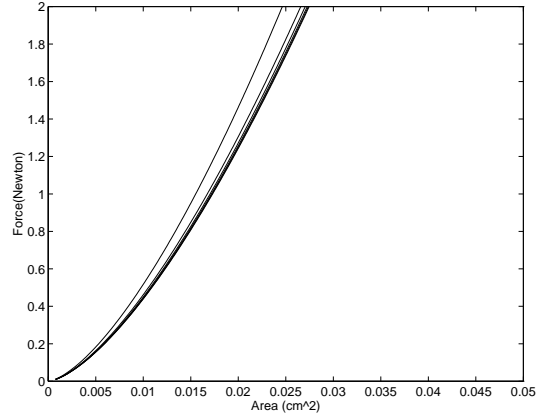

Figure 4: Contact force/area curves for the hertzian model of contact between a finger as above, and six specimens with $\nu_2 = 0.5, E_2 = 0.125MPa$, and R_2 ranging linearly between $5R_1$ and $50R_1$.

By substituting the expressions for $\overline{u}_{z_1}$ and $\overline{u}_{z_2}$ in equation 1 we get

$$\frac{\pi p_0}{4aE^\star}(2a^2 - r^2) = \delta - \frac{r^2}{2R}. \tag{4}$$

where $\frac{1}{E^\star} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}$, and E_i denotes the Young's modulus of the i–th body. From Eq. 4 the radius of the contact circle is obtained as

$$a = \frac{\pi p_0 R}{2E^\star}. \tag{5}$$

The total force compressing the bodies being related to pressure by

$$F = \int_0^a p(r)2\pi r dr = \frac{2}{3}p_0\pi a^2, \tag{6}$$

using equation 5 we can relate the area of the contact disk A to force F as

$$A = \pi a^2 = \pi \left(\frac{3FR}{4E^\star}\right)^{\frac{2}{3}}. \tag{7}$$

Contact between a "finger" with given elastic and geometric parameters E_1, ν_1, R_1 and "specimens" with varying elastic coefficients yield different rates of spread of the contact area A with the contact force F, as illustrated in fig.3. The CASR obtained from equation 7 depends also from the geometry of the specimens. However, this dependence is weaker than that on the elastic coefficient, especially for specimens larger than the probing finger (see fig.4).

3 Implementation of CASR sensors and displays

In order for the CASR conjecture to be of practical value in remote haptic system design, two main ingredients are necessary: a psychophysical validation, and a practical implementation of sensors and actuators that could convey the CASR information. It should be noticed that CASR information is basically comprised of two time signals (force and area of contact) of analogic nature: this is to be contrasted with tactile information, where a time–varying spatial distribution of pressures need to be sampled in both time and space. Thus, at least in principle, sensing and actuation of CASR information should be much easier and faster. In this section, we describe very simple devices that may be implemented for realizing CASR transduction, which are used later for validation experiments.

3.1 CASR sensors

A first type of CASR sensor can be built using piezoelectric or piezoresistive materials. In both cases, a thin film of the material is covered with two conductive layers on opposite sides (see fig.5), and an electric signal (the electric charge or the resistance, respectively) is measured by suitable instrumentation (a charge amplifier or a Wheatstone bridge and differential amplifier, respectively). The charge displaced per unit area on the electrodes is related to mechanical pressure as $q = \alpha p^\phi$, where α and ϕ are characteristic constants of the material ($\phi = 1$ in the ideal linear case). Assuming uniform presure distribution, the total charge on the electrodes is $Q = \int q dA = \alpha p^\phi A$. An independent measurement of the total contact force $F = \int p\, dA = pA$ allows to derive a measure of the contact area as $A = \left(\frac{Q}{\alpha F^\phi}\right)^{\frac{1}{1-\phi}}$, hence to character-
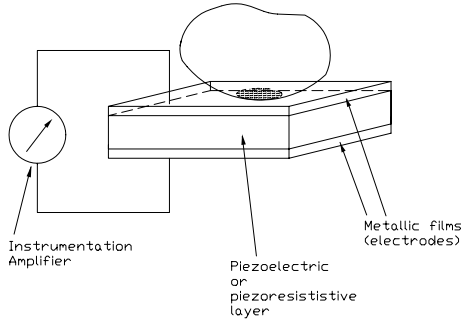
Figure 5: Schematic drawing of a piezoelectric or piezoresistive CASR sensor.

Figure 6: The optoelectronic CASR sensor used in our experiments.

Figure 7: Description of the CASR display.

ize the CASR curve. Analogously, in the piezorestive case, the unit area of the conductive rubber layer changes its resistance according to $r = \beta p^{-\psi}$, and, in the uniform pressure distribution assumption, one gets $A = \left(\frac{\beta}{RF^\psi} \right)^{\frac{1}{1-\psi}}$, where $R = \int r \, dA = \beta p^\psi A$ is the measured resistance. These formulas are to be considered as rough approximations of the real behaviour of sensors, where many effects (such as nonuniform pressure and shear effects) may be practically relevant [13]. In practice, experimental calibration of sensors would be necessary to obtain a tabulated CASR response. The above approaches to CASR sensing have the advantage of an extremely simple implementation, allowing for instance the realization of a contact area sensor on the tips of a laparocopic forceps with the need of a single wire to convey the signal (in this case, the force measurement could be provided e.g. by strain–gages that are already available in some instrumented tools, see e.g. [1]). The material used in the piezoelectric or resistive layer should be prepared so as to enhance its nonlinearity: the sensitivity of these sensors tends to zero as ϕ (resp., ψ), tends to unity.

Another approach to CASR sensing that directly measures the contact area would use optoelectronic components to remotely measure changes in illumination due to changes of contact area. An example of optoelectronic CASR sensor is described in fig.6. The surface of the probing finger is realized with a transparent material (Plexiglas), and a LED/phototransistor pair is placed beneath the surface at a distance of few millimeters. The infrared LED emission is scattered over a wide cone, and is partially reflected at the interface of the finger with the outer environment. Reflection is negligible at points of the finger surface not contacting the probed object, while it is relevant at points belonging to the contact area. The phototransistor hence detects a signal roughly proportional to the contact area.

Although the optoelectronic CASR sensor may be somewhat complicate to build in miniaturized scale, it showed superior accuracy in our laboratory exper-
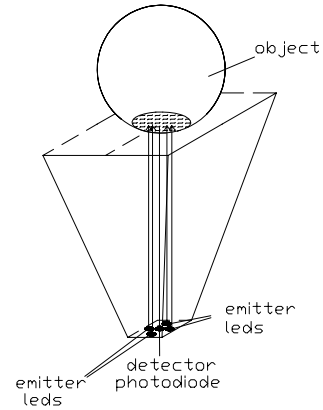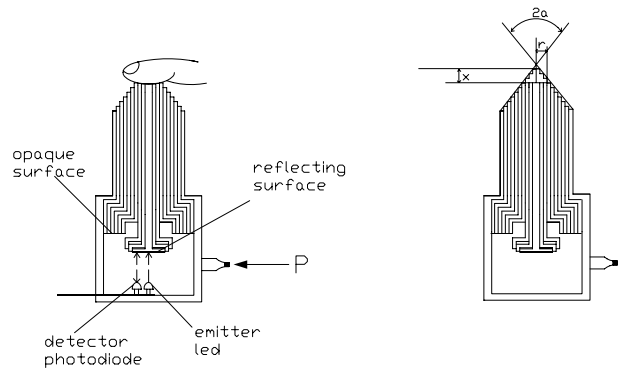
iments. For the purposes of the psychophysical tests to be described shortly, we built a CASR sensor of sufficient accuracy by carefully removing possible artifact causes. In particular, the reflective properties of different objects were equalized by spraying equal colours on their surfaces, and spurious sources of light from outside the sensor wher shielded accurately.

3.2 CASR display

The role of a CASR display is to replicate the rate at which the contacting area of the probed material spreads on the surface of the remote probing finger. A possible implementation of such behaviour is described in fig.7. The CASR display consists of a set of cylinders of different radii in telescopic arrangement. A regulated air pressure acts on one end of the cilinders. The operator finger probes the other end of the display. The length of the cilinders is arranged so that, when no forces are applied by the operator, the active surface of the display is a stepwise approximation of a cone whose total angle at the vertex is $2a$. When the probing finger is lowered by an amount
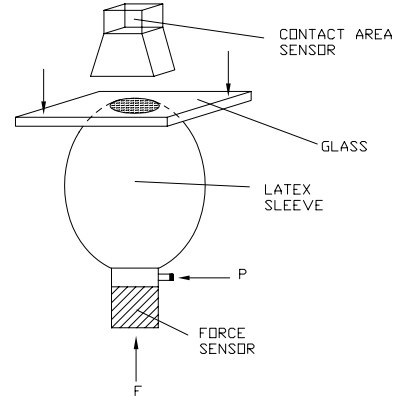
Figure 8: The prototype CASR display.

Figure 10: Variable softness device used in psychophysical experiments.
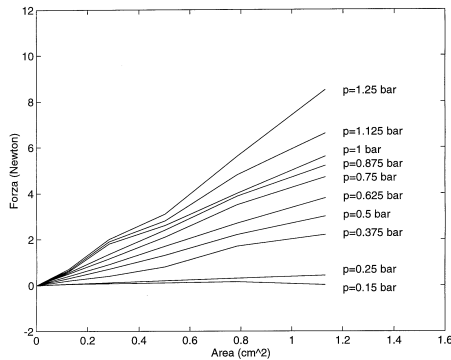

Figure 9: Force/Area response of the protype CASR display with constant pressure.

x, an area of contact A approximately evaluated as $A(x) = \pi x^2 \tan^2(a)$ is established. Correspondingly, the force opposed to the finger is $F(x) = PA(x)$, where P is the pressure established in the inner chamber by the external regulator. An optolectronic sensor placed within the chamber allows measurement of the displacement x, while a servo pneumatic actuator regulates the chamber pressure based on x and on the desired CASR profile to be replicated.

A laboratory prototype of the CASR display, with 10 concentric cylinders, is shown in fig.8, while fig.9 shows the experimental characterization of the CASR effect as measured with several different values of constant pressure P.

3.3   Experimental results

To validate, at least preliminarily, the CASR conjecture, we devised and executed a psychophysical experiment, which has been conducted in our laboratory with the help of volunteers using the CASR sensing and displaying equipment above described.

The experiment consisted in measuring the capability of 15 volunteers to recognize 5 different items by touching a remote haptic system. Recognition rates using direct exploration, a kinesthetic display, and the CASR paradigm have been compared.

To do so, we collected 5 sets of data corresponding to the contact of a rigid surface with surfaces of decreasing compliance. In order to keep experimental conditions (superficial texture, colour, thermal properties of the specimens) as constant as possible in experiments with different items, we used a single device with variable softness (see fig.10). The device consists of an inflatable thick Latex sleeve, of which the apparent softness is varied by changing the internal air pressure.

The first phase of the experiment consisted in pressing a flat glass surface against the upper portion of the sleeve and in gathering, for 5 different levels of internal pressure in the sleeve, data concerning the contact force (measured by a load cell shown in fig.10), the displacement, and the area of contact (measured by an optoelectronic sensor through the compressing glass). In the second phase of the experiment, volunteers wearing surgical latex gloves have been allowed to practice in touching the latex sleeve at the 5 different levels of softness, which were labeled as "item 1" through "item 5". After what was subjectively considered a sufficient training, volunteers explored the CASR display described in a previous section, while the display pressure was controlled in such a way that its contact area would spread, in contact with a rigid surface, at the same rate as one of the sample items. Volunteers were asked to guess which item the display resembled the best. This procedure was iterated for all items in random order. Analogously, volunteers were asked to explore a purely kinesthetic display, and report on their associations with different items. The kinesthetic display was realized by simply covering the
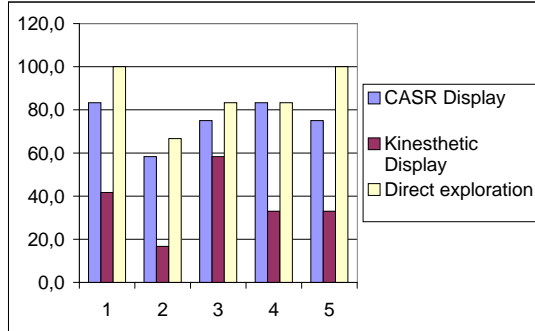
Figure 11: Percentage of successfull recognition of 5 different levels of softness by direct exploration, and CASR and kinesthetic haptic displays.

CASR display with a hollow cylinder, whose upper base is flat and rigid. The display is controlled in this case so as to replicate the displacement/force behaviour of the items. Finally, volunteers were asked to perform recognition of different items by exploration of the original items themselves, presented in random order. Results of the three sets of data concerning correct recognition of different levels of softness are reported in fig.11. It can be observed that recognition using the CASR information outperforms pure kinesthesia, and provides results comparable with direct exporation of items.

4 Conclusions

It has been firmly established in the psychophysical literature that the ability of discriminating softness by touch is intimately related to both kinesthetic and cutaneous tactile information in humans. In replicating touch with remote haptic devices, there are serious technological difficulties to build devices for sensing and displaying fine tactile information. In this paper, we investigated the possibility that a simplified form of tactile data could convey enough information to allow satisfactory discrimination of softness, while allowing practical construction of devices for practical applications. Results of our psychophysical experiments, albeit preliminary, encourage this conjecture.

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