Tactile Flow and Haptic Discrimination of Softness

Antonio Bicchi, Enzo P. Scilingo, Davide Dente, and Nicola Sgambelluri

Centro Interdipartimentale di Ricerca "E. Piaggio", Università di Pisa, Italy
<bicchi, e.scilingo, d.dente, n.sgambelluri> @ing.unipi.it
http://www.piaggio.ccii.unipi.it

Summary. Haptic perception involves both cutaneous perception, through mechanoreceptors lying on the skin, and kinaesthetic perception mediated by the position of the fingers. Analogously, artificial devices should replicate both these perceptual channels, as well. While kinesthetic information is satisfactorily replicated by current technology, cutaneous information is still a challenging task to be provided. In order to comply with this goal, a computational model of perceptual flow, inspired to established models for vision, has been recently extended to the tactile domain. It has been shown that tactile flow encodes important information on relative motion and segmentation of tactual scenes. In this paper we illustrate how previous results on the "contact area spread rate" with softness detection can be conveniently explained in terms of integral of tactile flow over the contact area.

1 Introduction

In the analysis of human and artificial vision, optic flow has been widely recognized to be crucial in fast sensorimotor coordination and feedback. Optical flow is basically an abstraction of raw data coming from the sensor (retina or camera), that extracts information on the relative velocity of the sensor and the visual target by observing how fast the target image grows over time. Different image sequences may have identical optic flow, so that there is a loss of information. However, optic flow of artificial images can be easily computed, and this information has been successfully used in several applications (for instance, in estimating the time-to-contact for automobiles proceeding in a line, thus enabling collision avoidance strategies). On the other hand, experimental evidence has been obtained through Functional M.R.I. techniques that some cortical areas are specifically excited by optic flow, thus proving that it is deeply rooted in human psychophysics. In this paper, we inquire into the existence of a similar concept in a different sensorial domain, that of tactile perception. The goal of such investigation is twofold: on one side, there is a fundamental interest in the psychophysics of a less-explored perceptual channel such as touch; on the other hand, many possible fallouts may ensue in disciplines where a sensorial substitution and simplification would be important: haptic displays for VR and prosthetics are two examples. In particular, we are interested in establishing whether a description of "tactile flow" can be given that codifies important information for manipulation operations; is amenable to implementation in haptic displays and/or prosthetics, and has a connection to the psychophysics of touch in humans. Some of these questions have a positive answer, while others are still open, even though we have encouraging preliminary results. We will show how tactile flow can be defined in terms of the displacement of iso-strain curves on the surface of bodies in contact at varying the overall compression force, and how this definition is consistent with the "Contact Area Spread Rate" observed under increasing load. In particular, the strict analogy between the time to contact paradigm in vision and the tactile flow in touch was explored.

2 Optic flow: a review

Any image can be segmented in a set of pixels. To each single pixel is associated a single intensity value, which itself is the result of many factors, as the intensity, color, reflectance, etc. This intensity value can be detected by a local measure at each spatial point (E(x,y)). During a movement a sequence of images is produced. By extracting two images separated by a discrete time interval, it is possible to define *optic flow* as a vector field describing this intensity change by indicating the motion of features from one image to the other one. In other words, optic flow [1] is the distribution of apparent velocities of movement of brightness patterns in an image that arises from relative motion of objects and a viewer or from changes in light sources. The human brain analyses this flow field to obtain several information about the environment. The optic flow field contains proprioceptive, segmentation and exteroceptive information [2]. Proprioceptive information refers to both rotational and translational egomotion and orientation. Segmentation regards splitting and merging scene zones on the basis of flow discontinuities. Exteroceptive information concerns position, motion, form and orientation of objects. In robotics, optic flow may be fruitfully exploited to recover scene depth, detect object trajectories, avoid collisions. It is also experimentally proved that an area in human cortex responds specifically to optic flow revealed by fMRI (functional magnetic resonance imaging) [3].

A traditional technique to calculate the optic flow is the assumption that the total spatial and temporal derivatives of the images brightness remain constant. Let $E(x, y, t)$ denote the brightness at time t of an image point (x,y). If $u(x, y)$ and $v(x, y)$ are optic flow components x and y at that point, and under the assumption that image brightness in each image point is stationary with respect to t, then we will expect that brightness is the same at time $t+\delta t$ at point $(x + \delta x, y + \delta y)$, where $\delta x = u\delta t$ and $\delta y = v\delta t$. After time δt we can write :

$$E(x + u\delta t, y + v\delta t, t + \delta t) = E(x, y, t) \tag{1}$$

If the brightness change is small with respect x,y,t then the left-hand side of the equation 1 can be expanded in a Taylor series obtaining

$$E(x, y, t) + \delta x \frac{\partial E}{\partial x} + \delta y \frac{\partial E}{\partial y} + \delta t \frac{\partial E}{\partial t} + e = E(x, y, t) \tag{2}$$

where e contains the higher order terms which are assumed negligible. Simplifying the 2 and taking the limit as $\lim \delta t \to 0$ we obtain:

$$\frac{\partial E}{\partial x}\frac{dx}{dt} + \frac{\partial E}{\partial y}\frac{dy}{dt} + \frac{\partial E}{\partial t} = 0 \tag{3}$$

which is basically the expansion of the equation

$$\frac{dE}{dt} = 0$$

where the first term represents the total derivative of E with respect to time. Using the abbreviations

$$u = \frac{dx}{dt} \quad v = \tfrac{dy}{dt}$$
$$E_x = \frac{\partial E}{\partial x} \; E_y = \tfrac{\partial E}{\partial y},\, E_t = \frac{\partial E}{\partial t},$$

we obtain

$$E_x u + E_y v + E_t = 0. \tag{4}$$

The vector (u, v) is defined *optic flow*. The equation 3 is known as the optic flow constraint equation and defines a single local constraint on image motion. This equation is mathematically ill-posed because it yields one scalar equation in two unknowns. Let us consider a two dimensional space with axes u and v, which we shall call velocity space. Values of (u,v) satisfying the equation 3 are constrained to lie along a line in the velocity plane. Only the motion component in the direction of the local gradient of the brightness may be estimated, whereas nothing can be said about the component of the optic flow at right angles to the gradient, that is, along the iso-brightness contour. A graphical illustration of the computational definition of flow of iso-intensity curves is given in fig.1. Such incomplete definition of the flow is often referred to as the *aperture problem*, and is crucial in generating a few optical illusions.

3 Time to contact and tactile flow

3.1 Comparison between coding system used by visual and tactile modalities

Even though the sense of touch may seem very different from sight, there exist many similarities between them. When exploring the surrounding en-

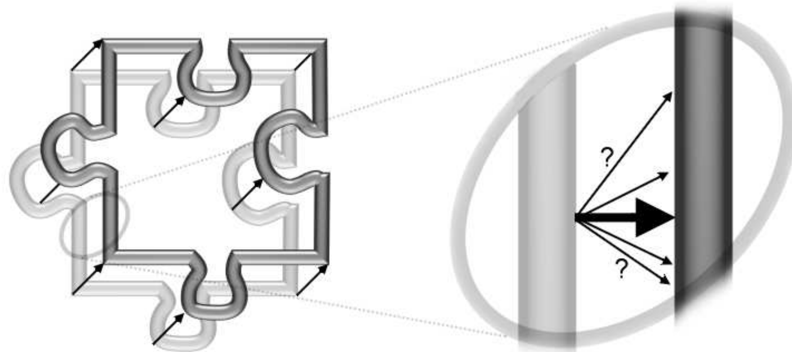

Fig. 1. An illustration of the concept of flow in the two-dimensional case. An iso-intensity curve of a certain level moves to a different position, defining a velocity field. However, having all points on the same curve the same intensity, it is not possible to distinguish their pair wise correspondence. This leaves the tangential component of velocities undefined, and gives raise to the so-called *aperture problem*, which in turn may generate perceptual illusions.

vironment touch and vision usually work together in a highly cooperative manner during the manipulation, apprehension and identification of objects. This cooperation is at the basis of the nature of multimodal perception and intersensory integration [4].

Vision is most often used to identify objects, although the tactile system is also useful. Haptics can provide information about the weight, compliance, and temperature of an object, as well as information about its surface features such as how sticky or slippery it is, information that is not readily available by merely looking at the object. However, even though haptics and vision both provide information about an object's volumetric shape, the modality of interaction is quite different. The receptor surfaces of both systems have regions of low and high acuity. For vision, the high-acuity region of the retina is the fovea; for haptics, the high-acuity regions are the fingers, lips, and tongue.

Physiologically, receptors codifying the images (cones and rods) are located at level of the retina. The neural coding of the visual information is conveyed from the retina to the *Lateral Geniculate Nucleus* (LGN) and the scene is analysed and vectorially split by means of the Ganglion Cells into many components, termed channels [5]. These channels are responsible for codifying relevant features of the image such as color, contrast and brightness. A first neural parallelism between touch and vision can be found by comparing the properties of the channels relating to hue, saturation of colour and intensity of light, to channels lying in the skin which give information about intensity of pressure, change of pressure and temperature. On the contrary, while skin uses many separate receptors to perceive different stimuli, the eye relies just on the rods and cones and the information is obtained through analysis. Nevertheless, since the code system used by the mechanoreceptors is still under investigation, the hypothesis that skin uses a similar analytical mechanism cannot firmly excluded. In addition, in the LNG there exists additional complex cells which use a tree-like structure analysis of the image to detect the presence of edges and objects moving in a given direction, as well as the spatial frequency of the stimulus. A similar pattern also exists in the haptic mechanism of perception. Another analogy is based on the lateral inhibition analysis. In haptic perception it was experimentally shown that monkeys and man both exhibit lateral inhibition to increase sensory acuity, i.e. some receptive fields on the skin are linked to Ganglion Cells in such a way that they respond to a specific stimulus. This mechanism also exists in the visual system. For example, an object of a specific size may stimulate a separate single channel. A strict analogy can be also found between the stimulus of contrast codified by the eye and the contrasts in pressure codified by the haptic modality [6]. Moreover, many similarities in neural coding between the two senses appear evident in the several experiments performed on blind people. Through brain-mapping techniques of investigation, it was found that when a blind person is given a touch stimulus, the pathways to visual cortex are activated as well as the normal pathways. If a normal person with eyes closed performs the same task, the visual cortex does not display such activity. This means that in blind people the touch sense provides surrogating sensations for the sight. This confirms that information in both senses are codified in similar way.

3.2 The new paradigm: tactile flow

Our hypothesis is that there might exist a tactile concept similar to optic flow. In a previous work [7] authors have proposed a new psychophysical hypothesis to convey haptic information. In particular it has been conjectured that a large part of haptic information necessary to discriminate softness of objects by touch is contained in the law that relates resultant contact force to the overall area of contact, or in other terms in the rate by which the contact area spreads over the finger surface as the finger is increasingly pressed on the object.

This new conjecture takes inspiration from the time to contact paradigm in the vision field. Time to contact is one application of optical flow, sometimes pessimistically referred to as time to collision or time to crash. Usually, when an object positioned at distance D from a camera moves with constant velocity v towards it, it will crash at time τ, called time to collision, $\tau = D/v$. If the relative motion occurs along the line of sight, i.e. the camera is translating but not rotating, and the environment is static, the flow field has a simple radial form (see fig.2). The center of the radial flow pattern is called Focus of Expansion (FoE). FoE gives the direction of motion in the visual frame of reference. In other words, the image of an approaching object expands.

In this case, only using optical measurements based on the optic flow and without knowing the velocity or distance from the surface it is possible to determine when the crash will occur. By processing the optic flow by means of suitable algorithms it is possible to infer the time to collision. In particular, it is sufficient to pick a point in the image and divide its distance from the FoE by its divergence from the FoE. An alternative viewpoint is to define the time to contact as the ratio between the visual angle between a point on the image and the FoE and the rate of change of this angle. Important implications of time to contact are in driving and avoiding collision, flying and landing and sports (boxing, football, baseball, ...). In the time to contact paradigm the iso-brightness contours move towards radial direction and the change rate of area comprised between two contours after a lapse of time is calculated as

$$\frac{dA}{dt} = \oint_{c(t)} \vec{\Phi} \cdot \vec{n} \, dl = \int \int_{A} \nabla \cdot \vec{\Phi} \, dA$$

where $\vec{\Phi}$ is the optic flow vector, $\vec{n}$ is the local versor perpendicular to contour.

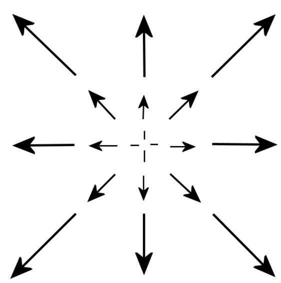

Fig. 2. Distribution of optic flow of an image moving forward.

It is noticeable a good resemblance between the growing rate of the contact area between the finger pad and an object during a tactile indentation task and the convergence or divergence of the vision field in time to contact task. In particular, the divergence from FoE of optic flow represents the expansion of iso-brightness contours. The area delimited by a closed iso-brightness contour grows with motion over time likewise the growth of the contact area in the tactile domain. This analogy led us to define a new conjecture, inspired to optic flow, which we called *tactile flow*.

The counterpart of iso-brightness curves in the tactile domain could be chosen between stress and strain profiles. Some evidence of this choice can be found by a psychophysical viewpoint. For instance, [8] shows that tactile information for stimuli increasing at a fixed rate, is more reliably conveyed when the stimulus is skin indentation rather than force intensity. In a similar spirit, experiments have been performed on mechanoreceptors in the racoon[9]. A likely analogy, hence, can be recognized between the divergence from FoE of optic flow and the spread of contact area superficial iso-strain profiles, which are concentric circles with center at the initial contact point, in the case of solids of revolution, during a mechanical interaction between two bodies (see fig.4). By analogy to iso-brightness curves in optic flow it is more convenient to manage a scalar rather than a tensor such as strain. A scalar strictly related to strain tensor is Strain Energy Density (SDE).

SDE is mathematically expressed by

$$U_{strain} = \sum C_{m,n} \varepsilon_n \varepsilon_m \tag{5}$$

where C is the stiffness tensor, and ε are components of the strain tensor. In analogy to the optic flow, we can define a 2D scalar field

$$U_{strain}(x, y, t) \tag{6}$$

Considering a contact between a pattern and a fingertip, the SDE at a particular point in the pattern changes spatially and with time. For small indentations we can assume that the spatial gradient of SDE is compensated by the time variation, such that the total differential remains unchanged. Hence, we can write

$$\frac{dU_{strain}(x, y, t)}{dt} = 0 \tag{7}$$

and expanding the above equation we obtain

$$\frac{\delta x}{\delta t} \cdot \frac{\partial U_{strain}}{\partial x} + \frac{\delta y}{\delta t} \cdot \frac{\partial U_{strain}}{\partial y} + \frac{\partial U_{strain}}{\partial t} = 0 \tag{8}$$

Even in this case, in analogy to the optic flow, the above equation can be called "tactile constraint equation", and it is affected by the tactile aperture problem as well. An experimental protocol is planned to be performed in order to verify the existence in the tactile domain of similar illusions to that related to the aperture problem of the optic flow.

When the fingerpad squeezes an object, by within the contact area it is possible to identify curves of iso-SDE. As the contact area spreads, the curves moves as well. We can associate to the contact area spread rate the flow of the iso-SDE curves.

We can define as tactile image a given iso-SDE curve. During a small indentation, tactile image moves to another one, generating an expansion or a contraction of the iso-SDE contours. The variation of the area comprised between two iso-SDE can be expressed as

$$\frac{dA_c}{dt} = \oint_{c(t)} \overrightarrow{\varphi} \cdot \overrightarrow{n} \, dl = \int\int_{A_c} \nabla \cdot \overrightarrow{\varphi} \, dA$$

where φ is the tactile flow, i.e. the velocity vector of the SDE.

Tactile flow, hence, can be associated to the Contact Area Spread Rate (CASR) paradigm. Indeed, we can assert that information codified by tactile flow is the compliance (softness perception) and it can be used to develop new haptic technologies.

4 Tactile flow and mechanical contact theory

As known from mechanical theory when two spherical objects come into contact the area around the initial contact point begins deforming. In such a way the mechanical interaction takes place on a finite smaller area than bodies dimensions. Contact theory predicts the shape of contact area and its behavior over time with increasing load. It allows to identify stress and strain components in both bodies within and outside the loaded area. Let us take a rectangular coordinate system with the origin as point of first contact in which the x-y plane is the common tangent plane the two surfaces (see fig.3).

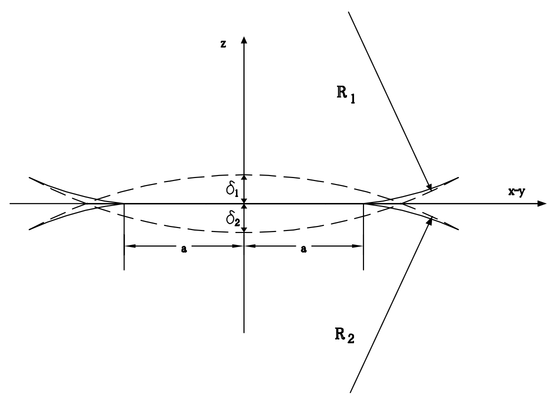

Fig. 3. Geometry of the contact area when two bodies come into contact.

Let us consider two points S_1 e S_2 on the surface of the two bodies having coordinates $S_1(x, y, z_1)$ e $S_2(x, y, z_2)$ before loading. The distance between them is given by:

$$h = z_1 - z_2 = \frac{1}{2}\left(\frac{1}{R_1'} + \frac{1}{R_2'}\right)x_1^2 + \frac{1}{2}\left(\frac{1}{R_1''} + \frac{1}{R_2''}\right)x_2^2 = \frac{1}{2R'}x^2 + \frac{1}{2R''}y^2 = Ax^2 + By^2 \tag{9}$$

where A e B are positive constants, R' and R" are defined as the principal relative radii of curvature.

It is possible to combine the previous radii introducing an equivalent radius of curvature defined as $R_e = \sqrt{R'R''} = \frac{1}{2}\frac{1}{\sqrt{AB}}$.

¿From equation 9 the profile of the distance h constant between unstrained surfaces are elliptical. When two bodies are brought into contact, distant points T_1 e T_2 move towards the origin O in parallel direction to axis z by displacements equal to δ_1 e δ_2 respectively. The contact pressure produces on the surface of each body a deformation in parallel direction to axis z by an amount u_{z1} e u_{z2} (positively measured within each body). If after loading S_1 e S_2 are coincident within the contact surface, then we can write:

$$\overline{u}_{z_1} + \overline{u}_{z_2} + h = \delta_1 + \delta_2 \tag{10}$$

Assuming $\delta = \delta_1 + \delta_2$ and substituting h by 9, the equation 10 becomes

$$\overline{u}_{z_1} + \overline{u}_{z_2} = \delta - Ax^2 - By^2. \tag{11}$$

If S_1 e S_2, after loading, are outside the contact area then

$$u_{z1} + u_{z2} > \delta - Ax^2 - By^2.$$

In the equations 9, if the two bodies coming into contact are solids of revolution then $R_1' = R_1'' = R_1; R_2' = R_2'' = R_2$, hence the equation 9 gets as:

$$h = z_1 - z_2 = \tfrac{1}{2R_1}x^2 + \tfrac{1}{2R_1}y^2 + \tfrac{1}{2R_2}x^2 + \tfrac{1}{2R_2}y^2 = \\ \tfrac{1}{2}\left(\tfrac{1}{R_1} + \tfrac{1}{R_2}\right)x^2 + \tfrac{1}{2}\left(\tfrac{1}{R_1} + \tfrac{1}{R_2}\right)y^2$$

which can be rewritten as

$$h = Ax^2 + By^2$$

obtaining

$$A = B = \frac{1}{2}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

Substituting

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$$

and writing it in polar coordinates ($x^2 + y^2 = r^2$) the equation 11 becomes

$$\overline{u}_{z_1} + \overline{u}_{z_2} = \delta - \frac{1}{2R}r^2 \tag{12}$$

When a pressure is applied to two bodies, the contact point spreads into a circular area and profiles of constant separation between the two surfaces before loading are circles centered at the origin O as well. According the Hertz theory [10] the pressure exerted onto two solids of revolution in contact is

$$p(r) = \frac{p_0}{a}\sqrt{(a^2 - r^2)}$$

and the total pressure is

$$P = \int_0^a p(r) 2\pi r dr = \frac{2}{3} p_0 \pi a^2.$$

Such a pressure produces a normal displacement of surfaces points, within the loaded area, respectively:

$$\overline{u}_{z_1} = \frac{1-\nu_1^2}{E_1} \frac{\pi p_0}{4a} (2a^2 - r^2) \qquad r \leq a \tag{13}$$

$$\overline{u}_{z_2} = \frac{1-\nu_2^2}{E_2} \frac{\pi p_0}{4a} (2a^2 - r^2) \qquad r \leq a \tag{14}$$

Let us introduce the equivalent quantity

$$\frac{1}{E^*} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}$$

The equation 12 can be rewritten as:

$$\frac{\pi p_0}{4aE^*} (2a^2 - r^2) = \delta - \frac{1}{2R} r^2 \tag{15}$$

where substituting $r = 0$ we obtain:

$$\delta = \frac{\pi p_0 a}{2E^*}$$

Moreover, placing in the same equation $r = a$ we can obtain the radius of contact area:

$$a = \frac{\pi p_0 R}{2E^*}$$

Tangential displacement, which is with radial symmetry as well, is given by:

$$\overline{u}_r(r) = \frac{(1-2\nu)(1+\nu)}{3E} \frac{a^2}{r} p_0 \left[1 - \left(1 - \frac{r^2}{a^2} \right)^{\frac{3}{2}} \right] \qquad r \leq a \tag{16}$$

The radial superficial strain component is:

$$\overline{\epsilon_r} = \frac{\partial \overline{u}_r}{\partial r}$$

hence

$$\begin{aligned} \overline{\epsilon_r}(r) = -\tfrac{1}{3Er^2}(-1+2\nu)(1+\nu)p_0(-a^2 + a^2\sqrt{\tfrac{a^2-r^2}{a^2}} + \\ +2r^2\sqrt{\tfrac{a^2-r^2}{a^2}}) \end{aligned} \tag{17}$$

Contours in 3D plots are reported in fig.4. The projection of these contours on a plane results in concentric circles likewise the iso-brightness contours of an objects moving forward a camera.

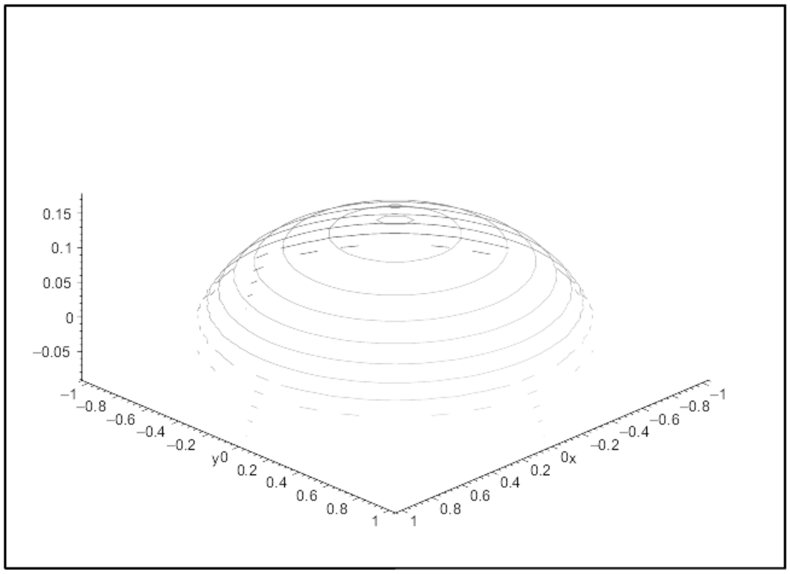

Fig. 4. Plot 3D of the radial component of the isostrain curves.

5 Conclusion

In this paper a new psychophysical hypothesis in the tactile domain inspired to optic flow in vision has been proposed. Optic flow has been widely recognized to be crucial in several applications. In particular, computation of optic flow of artificial images provide useful information for many fields of applications, for instance, in estimating the time-to-contact for automobiles proceeding in a line, thus enabling collision avoidance strategies. Here time to contact paradigm has been analysed and the mental process leading to formulate the conjecture of tactile flow has been described. Finally, the tactile flow was investigated in terms of distribution of stress-strain profiles during the mechanical contact between two bodies.

References

1. Gibson J. J. :The perception of the visual world. Boston: Houghton Mifflin, 1950.
2. Barron J.L., Fleet D. J. and Beauchemin S. S.: Performance of Optical Flow Techniques. IJCV (1994), 43-77.

3. M. C. Morrone, M. Tosetti, D. Montanaro, A. Fiorentini, G. Cioni and D. C. Burr: “A cortical area that responds specifically to optic flow, revealed by fMRI”. *Nature Neuroscience*, vol. 3 no. 12 pp. 1322-1328, December 2000.
4. S.J. Lederman and R.A. Browse: ”The physiology and Psychophysics of touch”, *Sensors and Sensory Systms for Advanced Robots*. Springer-Verlag Berlin Heidelberg, 1988.
5. E. B. Goldstein: “The Cutaneous Senses” Ch.14,*Sensation and Perception*, 3rd Ed., Wadsworth Publishing Company (Belmont CA, reprinted 1989).
6. P. Whittle, *Haptic Perception*, as part of NST IB Experimental Psychology 1989-99 lecture handouts, University of Cambridge (Cambridge, 1998).
7. A. Bicchi, D. De Rossi, E. P. Scilingo: The role of the contact area spread rate in haptic discrimination of softness. IEEE trans. on Robotics and Automation (2000) 16(5): 496-504.
8. J.D. Greenspan: ”A Comparison of Force and Depth of Skin Indentation upon Psychophysical Functions of Tactile Intensity *Somatosensory Research*, Vol. 2, No. 1, 1984, pp. 33-48.
9. B. H., Jr. and L. M. Pubols: ”Magnitude scaling of displacement and velocity of tactile stimuli applied to the human hand”, *Barin Res.*, 233:409-413.
10. K. L. Johnson: ”Contact mechanics”, chapter 4, Cambridge University Press 1985.