Tactile Edge Detection

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***Abstract*— The mechanics of the skin and subcutaneous tissues are as central to the sense of touch as the optics of the eye is to vision and the acoustics of the ear is to hearing. Recent published theories of the functional morphology of glabrous skin micro-structures and their associated nerve endings are developed in this paper to form a new concept, that of direct tactile edge encoding by the skin. Through exploiting key mechanical properties and structures of human glabrous skin, it has been possible to create a prototype edge-encoding tactile sensor with an artificial skin capable of high levels of compliance, conformability and strength. The sensor has proved to have an impressive level of sensitivity, accuracy and detail within a skin design that promises to be a capable and practical end-effector. This paper presents and discusses the edge-encoding function of the sensor design and presents results that illustrate the capabilities of the sensor concept and the importance of edge sensitivity in tactile sensing.**

I. Introduction

Tactile sensor designers have still not yet achieved the quality or sensitivity they have hoped for in a practical artificial fingertip and are far from matching the sensing capabilities of the human finger [1]. In working towards this target, researchers have repeatedly missed the key roles held by the mechanics of the skin and its natural sensitivity to edges [2]. The layered structure of glabrous skin of the human fingertip consists of a thin, flexible but strong epidermis surrounding a greatly contrasting highly compliant core that allows the high levels of compliance and conformability that are needed for sensitive and detailed tactile sensing. This compliance is constrained normal to the skin surface, as tangential shearing forces are resisted strongly by the epidermis in stretch [3]. With this level of 'constrained compliance', the skin can conform easily and sensitively, to very small surface details and features with minimal stretching, transducing these detailed skin defections to the corresponding tactile nerve ending. Recently, published theories about the mechanics of the Meissner's Corpuscle nerve endings are developed further in this paper, to form a new proposed direct edge encoding by these tactile nerve endings anded skin micro-structures. Edge information is as important in a tactile scene as it is in a visual one, allowing us to extract features, form and shape ffaces we touch. This theory of a tactile edge encoding functional morphology is reflected in the recognised importance of edges in the perceptual psychology of touch. However, the importance of edges in tactile perception has returned little focus in tactile sensor design to date.

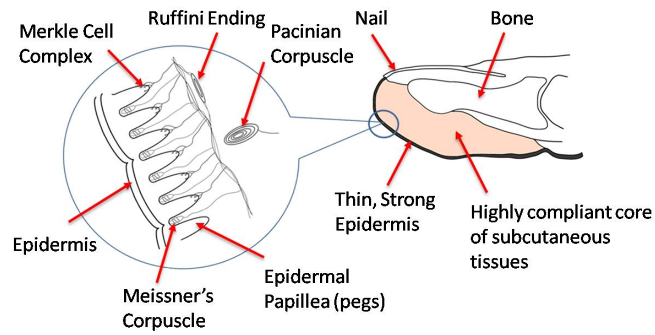

Fig. 1. Illustration of the fingertip skin in cross-section, with detail of mechanoreceptor locations and associated skin microstructures

II. Sensor Concept

Both vision and touch are well developed to be highly sensitive to edges. In vision research this has been prominent and its importance is clear within image and video processing. However, in tactile sensor design it is highly undervalued, even though edges are arguably as fundamental to touch as they are to vision. Both in touch and vision, edge information is used to define an object's shape and boundary, where one object ends and another begins, and where features are contrasted against a background. Although it is clear that human touch is heavily dominated by sensing edges, the mechanisms that create this sensitivity have so far not been made clear.

Fig.1 illustrates the layered skin structure of a human fingertip. Around the epidermal/dermal boundary is host to the four main mechanoreceptors in human skin; Merkle Cells, Meissner's Corpuscles, Ruffini Endings and Pacinian Corpuscles. These have specific locations within the skin, which has drawn the attention of engineering researchers in recent years. Through modern finite element analysis modelling techniques, theories have been produced to suggest that the epidermal pegs work to focus forces on the skin surface down to the Merkle Cell complexes located at their tips [4].

The conclusions of a study of the mechanical structure of the Meissner's Corpuscle, using modern imaging techniques [5], was developed further by Kuroki et al. [6]. Kuroki proposed that this mechanoreceptor actually responds to the horizontal strain produced from normal forces stretching the collagen fibres that anchoring it to the epidermal pegs, Fig.2 illustrates

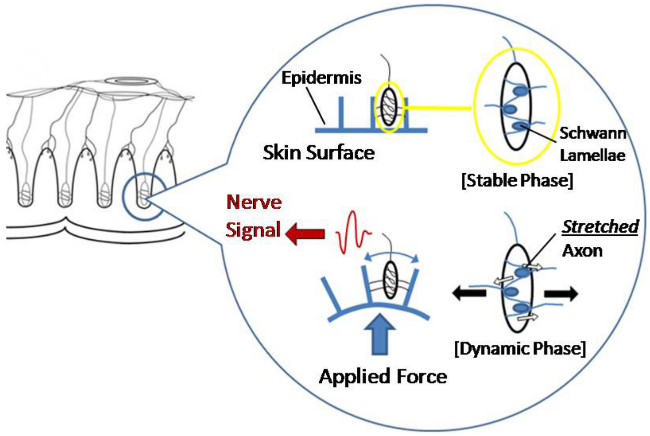

Fig. 2. Reproduced from Kuroki et al. 2008. Proposed stretch detection hypothesis of the Meissner Corpuscle. Forces applied to the skin surface separate the internal epidermal skin features, causing a stretching of the nerve axon and the signalling of the nerve ending

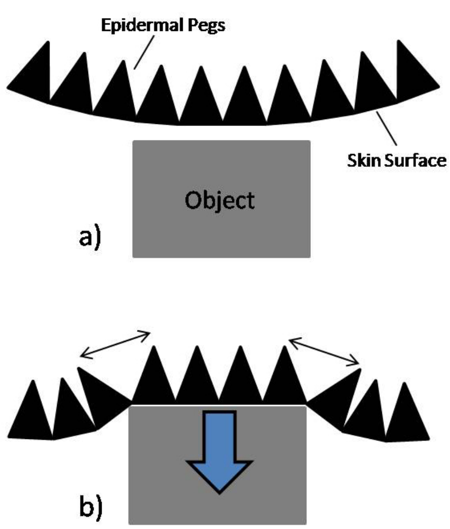

Fig. 3. A papillae featured skin, a), pressed against an object, b). As in the highly compliant skin conforms to the shape of the object, seperation of these skin features, and hence signaling of the Meissner's Corpsucle, would occur at locations of gradient changes of the conformed surface

this action. The Meissner's Corpuscles are located between the epidermal pegs, within the dermal papillae. When force is applied to the skin surface it causes the epidermal pegs to separate, pulling the anchoring collagen fibres and stretching the nerve axon, triggering a nerve response.

However, when looking at the skin as a whole, the skin, when conforming to an object surface, will produce different patterns of separation, depending on the changing gradients of the touched surface. Consider an area of featured layered skin pressed onto the object in Fig.3. The separations that produce the proposed Meissner's Corpuscles response are minimal on the flat of the object, and occur strongly at the edges, where the gradient changes cause transitions in the skin deflection.

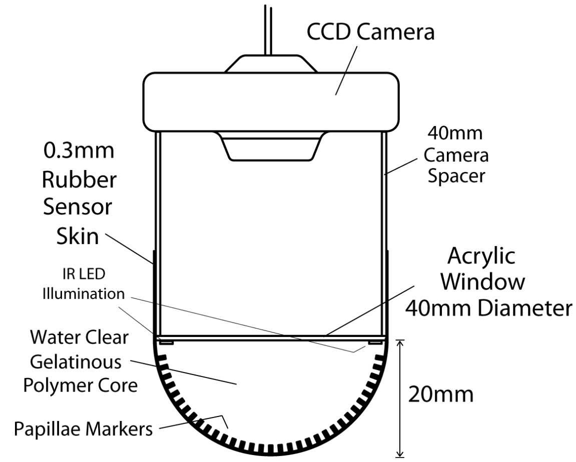

Fig. 4. Cross-section schematic of the sensor design

Thus, it can be said that the edge information of the object has been encoded within these epidermal features and that these mechanoreceptor nerve endings actually are responding to the horizontal stretch produced by edge features in a tactile scene. This relies heavily on the epidermis being of a thin, flexible and strong material in order to ensure that the skin flexes and conforms to, rather than stretching over, surface features. The core tissues give a highly compliant body to the finger pad, ensuring that the epidermis is pressed evenly into all the surface features, whilst still remaining highly sensitive to these local deformations. This edge encoding is a very sensitive process too; the highly compliant skin structure deflects easily under even very small forces and the lever action of these epidermal features serves to further amplify these surface deflections to the mechanoreceptor nerve endings.

III. Sensor Design

A prototype sensor was designed and constructed based on this proposed edge encoding function of human glabrous skin. It was important for the sensor's operation to maintain the high level of flexibility, conformability and constrained compliance that a layered skin would offer. If electronic sensing elements were to be placed under the skin of the sensor, the mechanics of the skin itself would be negatively affected. It would also prove to be a complicated and difficult construction to achieve a high level of resolution, with limited robustness for a practical fingertip end effector design. Thus is was decided that a CCD camera would be used internally, to view and track markers placed on a featured skin. Fig.4 show a cross-section schematic of the sensor design.

Fig.5 is a photo of the sensor in the vertical test rig stand.

The sensor design consists of a 0.3mm thick, 60 Shore A urethane rubber outer skin, cast into a 40mm diameter hemisphere pad with 1mm diameter, 1.5m high papillae-like features, uniformly spaced 2mm apart. The core of the sensor pad consists of a water clear melt-blend polymer that has an extremely high level of compliance and return to shape. A simple, 30 frames per second, 640 by 480, CCD camera

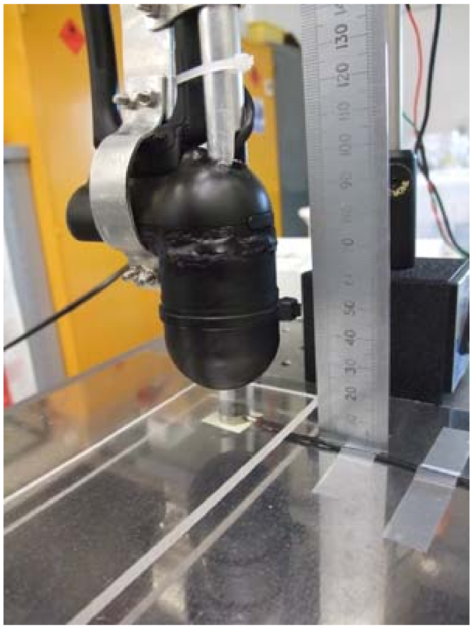

Fig. 5. Photograph of the sensor in its vertical test rig stand

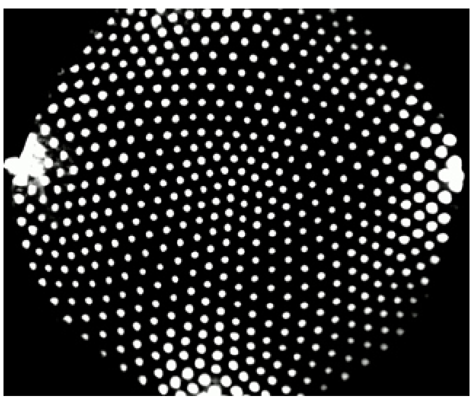

Fig. 6. An example of the camera view of the marker array at rest

was used, spaced by a 40mm with a plastic cylinder for the correct focal depth and field of view. Infra red LEDs were used internally to illuminate markers placed on the ends of the papillae-like features, in order for the cammera to view and track their relative displacements due to skin deflections. Fig.5 is an example view from the camera of the marker array.

The sensor skin is very compliant and conforms well to objects and surface features. It is also quite strong in shear and shows good promise as a practical end-effector, having a large contact area for a given force and strong relatively inelastic outer skin for gripping and manipulation. Edge features encountered by the sensor in touch cause the papillae-like features to produced separation patterns relative to the surface gradient changes causing the skin deflections, which are viewed by the camera, Fig.7. An example of the camera view of a touched object corner feature are shown in Fig.8. The camera video is processed using the MATLAB image

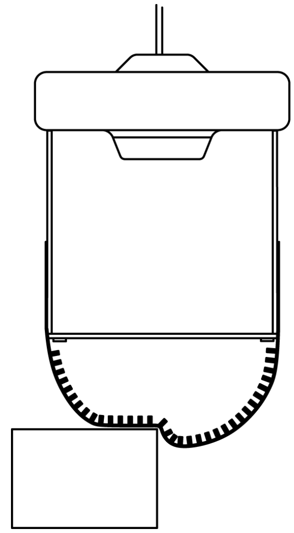

Fig. 7. An illustration of the sensor placed on an object edge

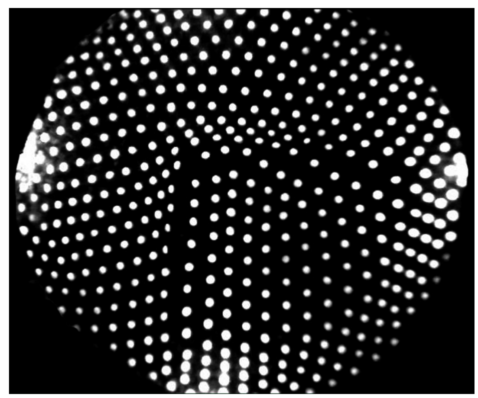

Fig. 8. An image from camera of sensor place on an object corner

processing toolbox, to find, track and analyse the patterns of movements of the markers. This use of a camera turns tactile stimulus into a visual processing task and allows for a range of well developed image processing techniques to be applied.

IV. Method

The video from the CCD camera was processed using the MATLAB image processing toolbox. The video frames first had a threshold applied and the marker centroids extracted from the image, the tracking of these centroids was maintained throughout the video. Since the sensor was so sensitive, the movement of these markers could be quite dramatic, so care and consideration had to be made in the tracking algorithms to ensure that markers were not lost. The markers on the skin are arranged in hexagonal patterns, i.e. each marker has six nearest neighbours in a hexagon pattern around it. The edge information in the video was extracted by calculating the resultant vector formed from the deformation of these six nearest neighbour patterns for each marker. A resultant vector indicates a non-uniform distortion of the marker pattern

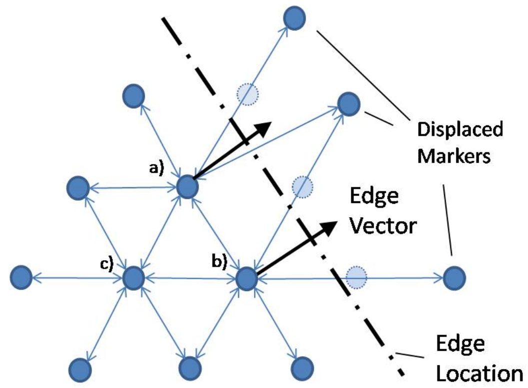

Fig. 9. For markers a), b) and c). a) and b) show how the resultant vector is formed from two of their nearest neighbours displacing non-uniformly relative to the others, caused by a straight edge. c) shows a uniform displacement of all markers and so has no edge vector

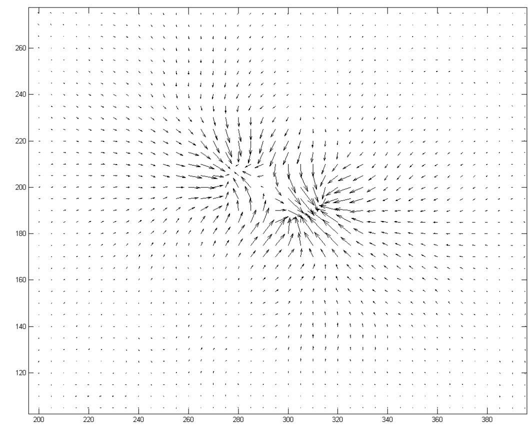

Fig. 11. Interpolated edge vectors for a two point discrimination 3mm apart

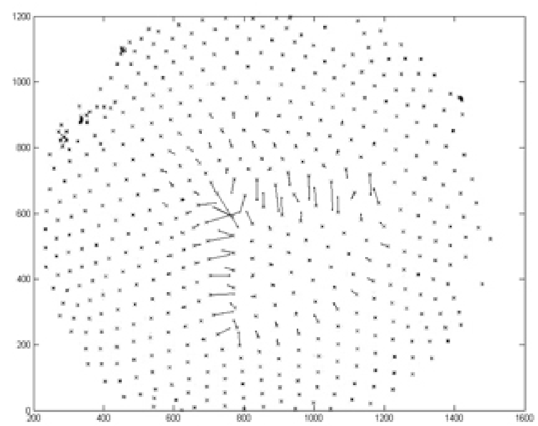

Fig. 10. An example of the calculated edge vectors for a corner object edge

resulting from an edge. Uniform spreading occurs as a result of displacements towards the camera from none edge features. By edge features we mean gradient changes in the touch surface, the most pure form of which is the single point. In the case of an edge, the resultant distortion vectors all point towards the edge feature, of a length relative to the sharpness of the edge gradient, Fig.9 illustrates resultant vectors for an edge for three points.

The vector gradients, calculated for all points, therefore point towards an edge from markers from both sides, a corner edge vectors are shown in Fig.10. Therefore, a linear interpolation the edge vectors across the image forms a second derivative of edge gradient, with zero crossing occurring at the location of the edge. Fig.11 shows the linear interpolation of a two indenting points 3mm appart. In order to visualise the edge features, this interpolation result was gradient integrated to form a 3D surface representation a mapping of the edge information.

V. Tests

In the tests, the sensor was lowered vertically in a rig onto the sample objects in a test area to around 2.5N and static edge information was extracted from the sensor videos. The sensor was placed against various objects to examine the sensor's edge response in terms of detail and accuracy. The sensitivity of the sensor was also tested by use of a load cell, examining the sensors minimal measurable response to a single point indenter. Similar to human threshold testing, the sensor was put through a two point discrimination test, looking for the limits of minimal discernable separation of two point indenters. The sensors minimum detectable edge height threshold was tested but placing the sensor on across the edge of flat object of thin varying heights. Finally, the sensor's positional accuracy was tested by use of a single point indenter placed at a range of positions around the test area.

VI. Results

The test results showed that the sensor design has an impressive level of sensitivity, accuracy and detail. Limits of accuracy and senstivity tests were calculated using a minimal decernable difference measure against a noise measure, due to camera compression and image thresholding limitation. For example, the two-point discrimination limit was decided when the gap between the two points was minimally decernable above the average noise figure. This showed the sensor had a clear two-point discrimination of around 3mm and positional spacial accuracy of less than 0.5mm was recorded, more detailed measurements were beyond the scope of the test rig. The sensor detectably reacts to forces as low as 0.03N and can apply forces in excess of 10N whilst still maintaining complete edge detail. The impressive detail was demonstrated in the sensing of a standard sized Braille character 'n', as shown in Fig.12 The results showed that the sensor can also reacts to edges down to 0.3mm in height. Examples of level of edge detail and shape sensitivity are illustrated in Fig.13, Fig.14 and Fig.15, where the edge location and shape of two coins, though they were placed together under the sensor at only

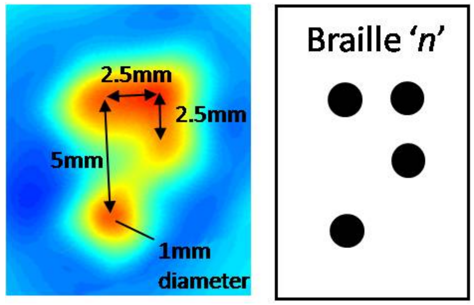

Fig. 12. Example edge plot of the sensor placed on a standard size Braille character ’n’

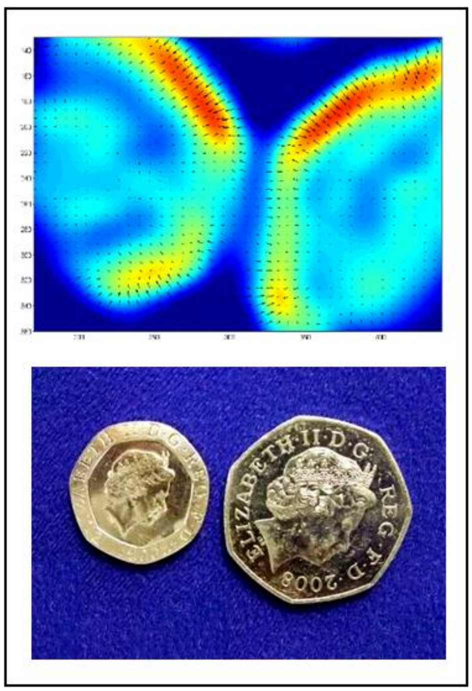

Fig. 13. Example edge plot of the sensor placed on two British coins (a 20p and an 50p) placed 3mm apart

3mm apart, is clearly visible in Fig.13. In Fig.14, a 1mm ball-bearing is clearly visable within an annulus of a 13mm outer, 7mm inner diameter washer.Fig.15 shows the sensor’s level of detail by picking out the features of a door key, including the centre trench area.

VII. Conclusion

The concept of an edge encoding functional morphology of the microstructures of the skin is very interesting. It could have great implications for the study of perceptual psychology of touch and the functional roles in neurophysiology. This prototype sensor has illustrated practically how such an edge encoding may be working in the skin. Humans are particularly sensitive to edges, in current thinking; it is believed that the Merkle Cells alone are the main produces of curvature and edge sensitivity. This research added an interesting dimension to this and raises the possible prominence of the Meissner’s Corpuscle in the role.

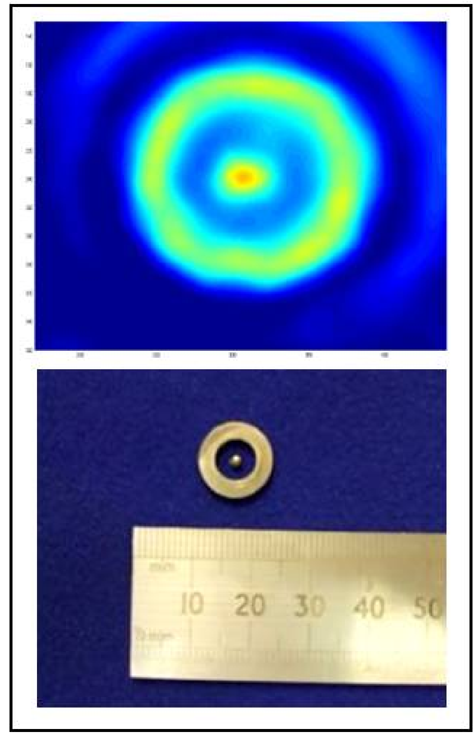

Fig. 14. Example of a edge plot of the sensor output for a 13mm outer, 7mm inner diameter annulus, 1mm high, with a 1mm ball-bearing in its centre

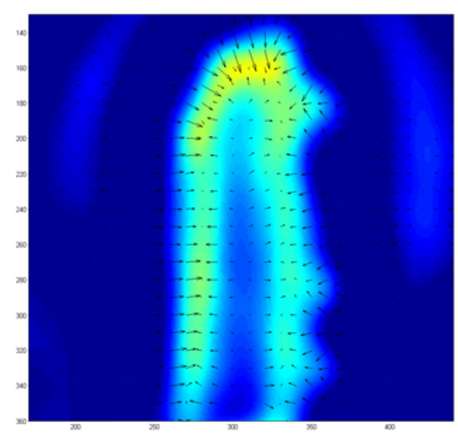

Fig. 15. Example edge plot of the sensor placed on a door key head

For tactile sensor design, this edge encoding by the sensor skin allows for a sensitive and detailed edge filtering direct from the skin. Edge filtering, as in visual processing, allows for object boundaries and features to be extracted. More than that, in tactile sensing it allows for a high level of sensitivity to small features and details, allowing the sensor to discriminate well between two point features, or edge shapes of an object. Edges are very important to touch in not only discerning important object features, but also properties such as roughness or smoothness. There is a lot of future research to be done examining the dynamic properties of this sensor concept, and how movement allows for greater sensing detail and the examination of object properties just as texture and compliance.

The biologically inspired layered skin structure has allowed the sensor to be highly compliance and conformable, meaning it is not only a highly sensitive and detailed sensor, but has large contact surface areas for a given force. This gives a great area of sensation as well as aiding grip and manipulation when advanced into a practical end-effector design. Further work has involved the mechanical characterisation of the sensor skin properties, for both sensing and grip, and the development of further processing algorithms to extract force distribution, through uniform marker spread, and the detection of shear and torque, through 'flock movements' of the marker array.

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