Development of a Tactile Sensor Based on Biologically Inspired Edge Encoding

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***Abstract*— Here we present a novel biologically inspired tactile sensor based on the structure of the human fingertip. Unlike previous biologically inspired sensors, it is based on new theories of the functional morphology of the fingertip skin features and the Meissner's Corpuscles mechanoreceptors pervading them, particularly in the encoding of tactile edge information. Through mimicking the layered macro-structure of fingertip skin the sensor is highly conformable and very sensitive, as well as a strong and practical gripping tool. The tactile sensor is composed of a thin flexible rubber skin with structural details emulating those of the glabrous epidermis. This encases a clear, highly compliant polymer melt blend with similar mechanical properties to the dermis and subcutaneous fat. A camera is used to track markers on the internal structural details of the rubber skin enabling remote, detailed, direct and sensitive detection of surface deflections. Initial results presented here show the design to be a very capable, highly sensitive sensor as well as a very practical, affordable and scalable robotic fingertip.**

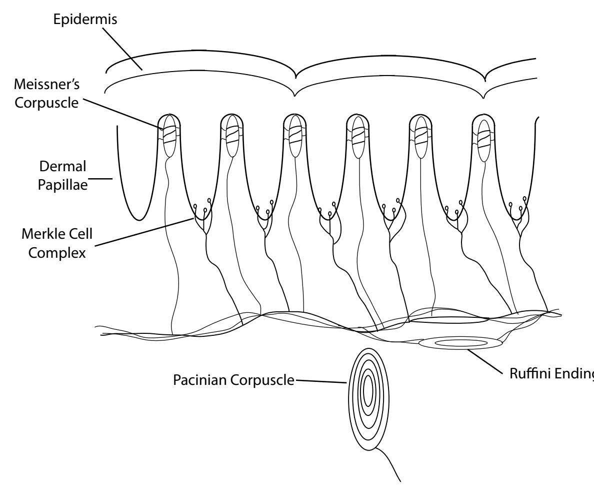

Fig. 1. Cross Section Illustraion of Glabrous Skin

I. INTRODUCTION

Investigations into the functional morphology of the human fingertip have produced some significant results for robotics research in tactile sensor design.

A. Biologically Inspired Sensors

Tactile sensing in robotics has traditionally taken matching the human example as its ultimate goal[1]. It is only natural then to look to biology for inspiration. Previous biologically inspired sensors have tried to gain advantages from mimicking the physiology of the skin, or the function of the nerves, to greater or lesser extents.

It is taken that, of the four tactile mechanoreceptor nerve endings pervading the glabrous (hairless) skin of the palms of our hands and soles of our feet, the Pacinian Corpuscle, the deepest and largest tactile nerve ending, is the most attributed to the sensation of vibration. This has inspired many tactile sensor designs exploiting the vibrations created from explored textures, frictional properties of surfaces and in the detection of incipient slip of grasped objects[2]. Merkel Cells, however, can be seen to be sited at very specific locations on the tips of the Dermal Papillae, see Fig.1, on the epidermal/dermal boundary. Theories of the functional reasons for these Dermal Papillae in relation to the workings of the Merkel Cells have been derived from Finite Element studies of simulated fingertips[3]. It is believed that Merkel Cells respond to strain energy density due to forces deforming the skin, which is focused like a lens down through the papillae structure to these mechanoreceptor nerve endings. This functional morphology has inspired a few tactile sensor designs based around this lensing effect as a way of sensing applied surface force distribution, see Mukai[4] for an example.

It is widely accepted that the Meissner's Corpuscles are a rapidly adapting sensory nerve ending and have a reported sensitivity to vibrations between 10 - 60Hz. This, together with their proximity to the skin surface, has led to the general perception that they are purely a receptor of light touch vibration. However, a recent hypothesis of the workings of the Meissner's Corpuscle by Iwanaga[5] has shed light on the possible directional sensitivity of these Mechanoreceptors. Kuroki et al. built on Iwanaga's work and produced theories that the structure of the Meissner's Corpuscles, together with their location between the papillae, encode normal strain forces by detecting normal horizontal strain[6]. The work presented here attempts to illustrate that this functional morphology of the Meissner's Corpuscles, together with the Dermal Papillae, results in the encoding of edge information of a tactilely sensed scene.

B. Optical Based Tactile Sensors

There have been a number of vision based tactile sensor designs. Some of these make use of a ridged transparent internal layer acting as an optical waveguide. An external rubber cover skin is then deformed, with tactile pressure, against the waveguide causing Frustrated Total Internal Reflection, detectable by a camera. Early examples, such as Jiar et al.[7] and Begel[8], were so large the they could not realistically be used as a practical end-effector. This design concept, however, was further developed by Ohka et al. [9] to be of a more realistic size and shape. These designs can be seen to relate, to a greater or lesser extent, to the working structure of the Merkel Cell nerve endings. Some even make use of Dermal Papillae-like features on the rubber skin to cause detectable deformations of their tips against the waveguide, creating a detectable pressure distribution map of points.

The other main type of vision based tactile sensor use a camera to scan a pattern on an elastic surface that is then deformed with applied pressure. One of the most notable of this configuration is the GelForce sensor by the Tachi Lab, Tokyo[10]. Their design consists of two layers of dots, one red and one blue, within a clear silicon rubber. The relative movement of these layered dots, as the rubber is deformed, is captured by the camera and force magnitude as well as force vector information is calculated through elastic theory. They have also recently managed to scale this design down to a fingertip size[11]. These configurations, however, suffer from what is known as the Inverse Tactile Transduction problem. This arises due to the limited correspondence between the stresses deforming and displacing the markings deep within an elastic material, to those that are applied to the surface. The patterns of sensory data obtained by the camera may be a result of a combination of patterns on the surface. This is particularly relevant in fine detail discrimination as the elastic material acts as a low pass filter with only relatively large scale spatial patterns and forces transmitted through the elastic layer, attenuating any fine detail.

C. Skin Layers and Conformability

The structure of our fingertips plays important roles in our sense of touch and our ability to grip, manipulate and explore objects. Our specialised fingertip skin is both strong and highly compliant. This high compliance of the skin enables us to sense fine detail and light touch [12], while the layered structure of the thin, strong, inelastic but flexible epidermis, surrounding this very soft core, gives the glabrous skin its strength to grip, lift, explore and manipulate objects and aids the direct transmission of the tactile information to our nerve endings.

The importance of conformability and strength of the skin structure is often overlooked in sensor design. There is a preference to design for elastic deformation rather than inelastic conformability, or the use of a homogeneous semi-soft rubber as a compromise between compliance and strength, that neither has high strength nor high conformability[13]. Another of the problems found in tactile sensor design occurs when the sensing elements themselves have a detrimental effect on the desirable mechanical properties of the artificial skin. Copper wires, flexible plastic PCBs or other such electronics introduced into the contact skin area all contribute to affecting the mechanical properties and the sensor's achievable conformability. This attenuates the level of sensed detail possible and places these vital components where they are most likely to be damaged over time and use, often to result in a costly repair.

D. Edge Sensitivity

Our sense of touch is particularly sensitive to edges. By edges we mean the sharp gradient changes in the surfaces that we touch. These could be local raised points, as exploited in Braille, local features and textures or the actual edges and geometry of an object. This keen tactile sensitivity we have to edges highlights the importance edges have in all our fine control and understanding of what we touch; in exploring, manipulating, learning and recognising objects. Imagine trying to blindly place a square peg into the square hole without being able to the feel the shape of the peg, the shape of the hole or the ordination of the peg you are holding. Without edge information, it is hard even to imagine being able to find the locations of holes themselves. Rarely have tactile sensor designs considered sensitivity to edges as an important factor, though it is so prominent for us.

II. SENSOR OPERATION

As highlighted by Kuroki et al.[6], the Meissner's Corpuscles, positioned within the troughs of the Derman Papillae, Fig.2, have been recently theorised to be sensitive to lateral strain. Kuroki et al. wrote of this lateral strain (horizontal normal strain) as a result of a normal force causing movement of the papillae. However, when looking at the fingertip skin as a whole, this papillae movement occurs only where there is a change in gradient of the deflection of the skin surface. This movement and therefore the lateral strain the Meissner's Corpuscles detect, is actually proportional to the change in gradient of the deflection, not just simply a normal force. This results in an output directly proportional to the edges in a sensed scene.

Consider a finger pressing on a raised point on a flat surface, as depicted in Fig.3. The sharp gradient changes of the raise dot produces horizontal spreading and narrowing of the gaps between the papillae of the locally deformed skin. Where as the normal force applied by the flat surface is does not. This spreading and narrowing encodes the relative gradient changes that the raised dot produces. The flexibility and inelastic nature of the epidermis ensures the direct and sensitive transmission of this surface detail to the deflection of the skin and the movement of the papillae. If it were an elastic deformation, the detail would be lost in the stretching of the skin, creating the Inverse Tactile Transduction problem. The papillae also act as a stimulus amplifier as the local skin deflection is exaggerated by the papillae movement. A very similar affect has been exploited in the 'Tactile Contact Lens', where the movement of an

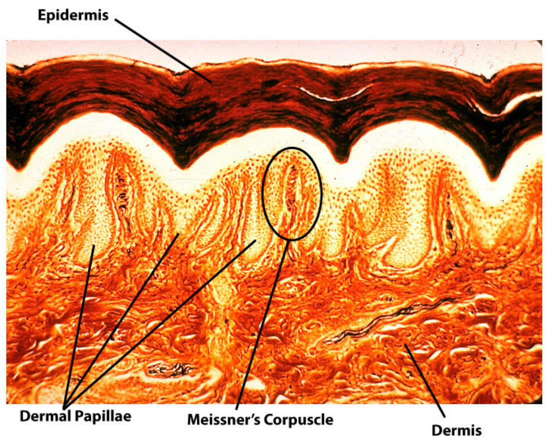

Fig. 2. Histology of Meissner's Corpuscles within Glabrous Skin

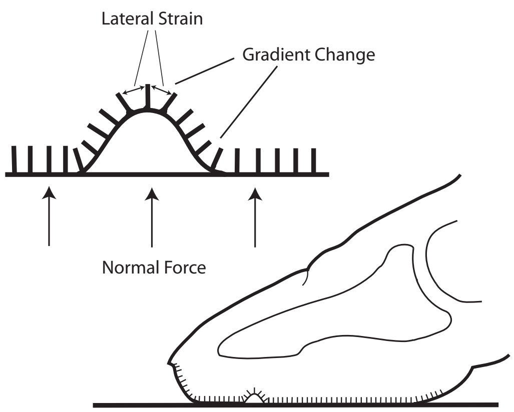

Fig. 3. Demostration of Papillae Edge Encoding

array of pins placed against a person's fingertip act to encode and amplify surface gradients, see Kikuuwe et al.[14]. The enclosed, highly compliant core of the finger pad ensures that the epidermis, pressed against the surface, conforms to the whole shape of the feature, enabling the maximum detail to be sensed.

A sensor could, therefore, be designed to mimic these papillae features on a strong, thin, inelastic, flexible rubber skin, and be used to sense surface deflections, with a particular sensitivity to edges, by detecting the relative movement of these artificial papillae. One method might be to integrate sensors into the skin that measure the relative lateral strain or movement of the artificial papillae. This would be very complex, very costly and adversely affect the skin's mechanical properties, also reducing the sensitivity and detail of the skin defections, as well as raising issues of reliability over time. With the use of markers on the ends of the papillae nodules, a camera can be used to track the entire skin remotely. This would mean the sensing surface and contact area of the skin is completely removed of wires or electronics, maintaining the desirable mechanical properties

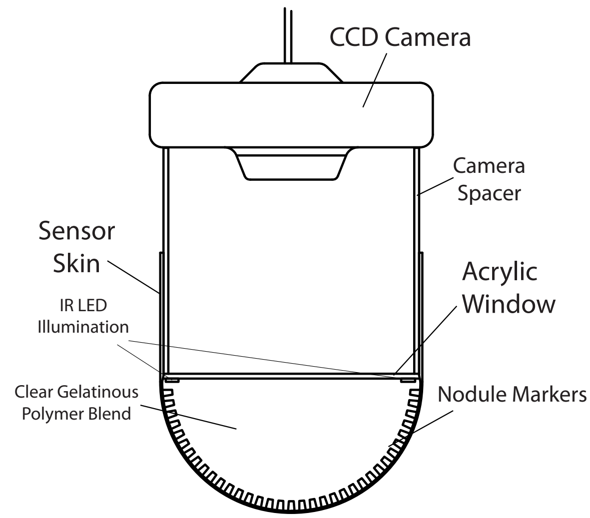

Fig. 4. Sensor Design

and robustness. Finally, an enclosed centre core, mimicking the very high compliance of the dermis and subcutaneous fat, would act to give the sensor its overall conformability, by forcing the flexible skin to match the surface detail when pressed against it. This results in a very capable and reliable sensor design with potential for economical manufacture.

III. Sensor Design

The sensor design consists of a 40mm diameter hemisphere of cast 0.3mm thick, black, Shore Hardness A 50 urethane skin. The thickness and hardness of the rubber ensures a very flexible but strong, relatively inelastic skin. The inside layer of the skin has an array of artificial papillae features that are 1.5mm high, 1mm wide and spaced 1.5mm apart, with white markers on the tips.

The hemisphere is filled with a water clear, very highly compliant, melt polymer blend and is sealed with a clear acrylic disk window. An arrangement of four infrared LED, around the inside circumference of the disk, is used to illuminate the markers. The skin is extended over a 35mm long plastic tube that acts as a focal length spacer and a mount for the camera. A 640 x 480 30fps CCD camera is mounted to capture the whole marker array. This set up gives, for this particular camera and lens, a focal distance of around 50mm for a 45mm wide field of view. For testing, the sensor was mounted vertically in a retort stand and lowered onto test indenters placed on a balance. This enabled measurement of the applied force compared to the resultant skin deflections, observed through the marker movement by the camera.

IV. Results

A range of indenter shapes and sizes were used to observe the reaction of the sensor.

Fig.5 illustrates an example of the reaction of the sensor to a single point indenter. On the left is the sensor at rest and

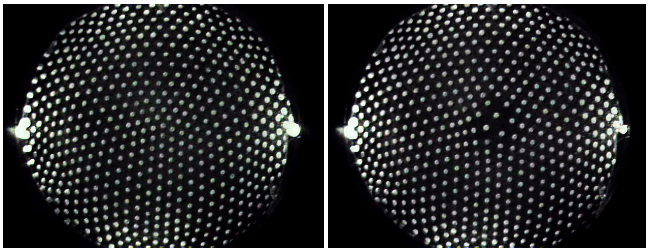

Fig. 5. Example of a 0.5N 5mm Diameter Point Force

the right as a result of a point, in this case, 5mm diameter and at force of 0.5N.

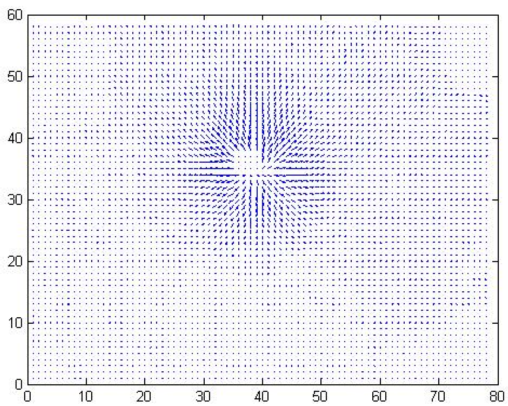

Fig. 6. Velocity Vector Field - 5mm Diameter Point, 0.25N Force

The point images were analysed using a velocity vector field to measure the relative pixel movement across the marker array. Fig.6 shows an example of the velocity vector field for a 5mm diameter point at 0.25N of force.

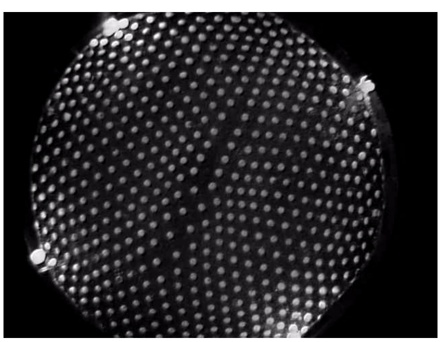

Fig. 7. Straight Edge

Fig.7 is an example of the reaction of the sensor to a straight edge indenting the sensor.

Fig.8 illustrates the reaction of the sensor to a annulus shape. The edge of the annulus is clearly visible, demonstrating the movement of the markers due to the changes in gradient across the shape. However, the circular shape is seen here as more of a pentagon pattern, due to the pentagonal layout arrangement of the nodules on the hemisphere.

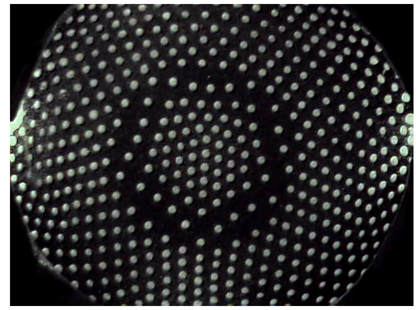

Fig. 8. Annulus Indenter

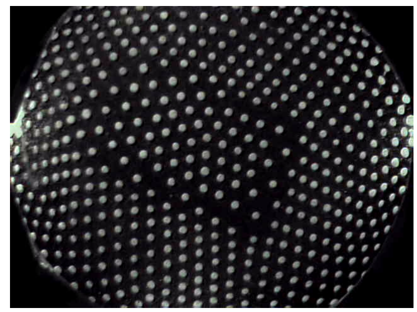

Fig. 9. Flat with Square Edge

Fig.9 is from an object that had a flat top and a sharp square edge. This example clearly shows the edge encoding in action, contrasting the reaction to a sharp edge to that of a flat surface.

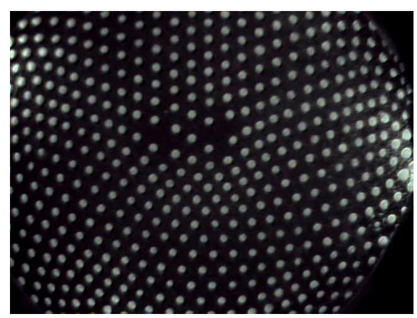

Fig. 10. Two Point Discrimination - 5mm Spacing, 0.5mm Diameter Point

Fig.10 shows an example of a two point discrimination test. Here the 0.5mm diameter indenters were spaced 5mm apart, producing a result clearly visible in the image. On the human fingertip, we can discriminate between two points at a minimum distance of 2-3mm. Considering the current relative size of the sensor, about four times that of a fingertip, this is quite an impressive result. Smaller two point widths are harder to see in a photographed image, however the future work on processing the image data will make a much more accurate two point discrimination possible.

Tests were then conducted to illustrate how sensitive the sensor could prove to be. A 0.5mm point indenter was applied at a force of 0.05N and processed by tracking the centroids of the markers, show in Fig.11, and with a velocity vector field Fig.12. The resulting detected movement was

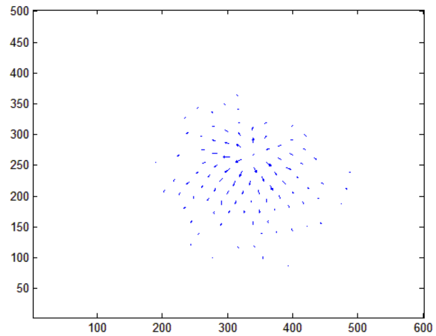

Fig. 11. Sensitivity Test - 0.5mm Point, 0.05N Force - Centroid Movement

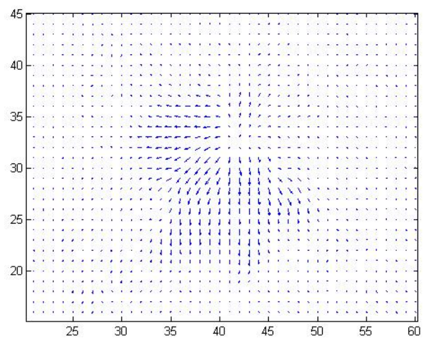

Fig. 12. Sensitivity Test - 0.5mm Point, 0.05N Force - Velocity Vector Field

clear in both cases. Further processing will increase this sensitivity as even a 0.03N applied force produces visually detectable movement of the markers.

In shear, the array of marker moves strongly relative to its direction, making shearing forces easily detectable also. As a whole, the biologically inspired layered design means the sensor also acts very successfully as an end-effector and gripping surface. The thin, strong outer skin encasing a highly compliant core enables a large, conformable contact area for a given applied force, a strong grip and the resistance to shearing forces needed in lifting and manipulating objects.

V. DISCUSSION

The results presented here clearly demonstrate the concept of edge encoding by the biologically inspired structures. This is particularly evident in the case of the flat rectangular object with sharp square edges, Fig.9. Here it can be seen that the forces normal to the sensor, due to the flat top surface, are not weak, contrasted against the strong reaction to its edges. If the functional morphology of the Meissner's Corpuscles is that they are sensitive to lateral strain; then this illustrates that, together with the Dermal Papillae, they may be working in this way to encode tactile edge information. This raises points about the source of our edge sensitivity and shows that the sensor produces an interesting new sensing modality, that of edge information. Further investigation into the camera output may show that is it is also possible to detect other mechanoreceptor related modes. Merkel Disc related information could be sought by looking at the size and shape changes of the markers, relating to pressure distribution. Overall movement would relate to shearing forces, most attributed to Ruffini's Endings.

Though the current results here are mostly images, they show the sensor to be very sensitive, demonstrating a detectable point force of 0.05N and showing promise of greater sensitivity with future processing. The two point discrimination tests illustrated that a 5mm gap between points can be seen in a static image, meaning a narrower point gap may be detectable in the future. Such a sensor system could be designed able to detect and determine one Braille character from another.

The nature of the sensor output is inheritly dynamic. The camera is there to detect the papillae movement and how the papillae move in reaction to a stimulus, gives up more information about the sensed object. As mentioned previously, Messiner's Corpuscles are rapidly adapting mechanoreceptors, there purpose is to be sensitive to changes in mechanical stimulus. As your finger is pressed or moved across an edge feature, more of the fine detail is revealed. Through suitable processing techniques focused on the dynamic nature of the sensor data, it is believed that greater detail, sensitivity and two point discrimination could be achieved.

VI. CONCLUSION AND FUTURE WORK

Here we have presented a novel tactile sensor for robotics. Through this sensor design it has also been possible to give a practical demonstration of new theories for the functional morphology of the structures within the glabrous skin of our fingertips and show how these might be exploited to create tactile sensors that can encode edge information. Sensitivity to edges is a vital part of our ability to finely manipulate objects as well as our ability to explore, investigate, learn and recognise them. A tactile sensor with this sensitivity to edges and the strength and conformability afforded to it by a layered skin should open new directions for tactile research. The results shown here demonstrate a clear ability to deliver edge information of various shapes and sizes. The current sensor design has shown a two point discrimination performance down to 5mm separation and sensitivity to forces of 0.05N or lower. The physical design is relatively simple, and could therefore be cheap, easy to produce and maintain, since there is no wires or electronics within the contact skin. The design relies on a moulding process that can be easily configurable and scalable to different sizes of sensor and papillae densities. This new sensor offers future robotics a very capable, affordable, scalable and practical tactile sensor design. The next stage of work is to investigate various different appropriate methods for processing the image data. The sensor response can then be characterised and calibrated. Further investigation into the dynamic characteristics will then follow, looking into the possible other sensor modes, of pressure distribition and shear, that may be possible to detect.

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