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Bio-inspired Flexible Sensing Technology for Next-Generation HMI: Ultrasensitive Crack-based Strain Sensors

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Abstract. The current stage of the development of the Human-Machine Interaction (HMI) systems, as rigid motion control systems, is replaced by an anthropomorphic sense of touch, forcing robot manipulators to have skin-like sensory abilities. But nowadays, flexible electronics are facing a fundamental dilemma of sensitivity versus stretchability. The paper will review the process of the ultrasensitive strain sensor design involving a bio-inspired micro-crack structure. It investigates the mechanotransduction of biological systems, first, to derive the theoretical basis of structural gating. Second, the paper investigates the application of modulus mismatch to stress concentration in arthropod-inspired designs. Third, the research explains the Disconnect-Connect model and the effects of quantum tunneling that make gating crack-based sensors so much higher than conventional limits to sensors. Lastly, the paper compares this technology with surface electromyography and finds that it has a better signal-to-noise ratio and latency in closed-loop control. The review states that structural bio-mimicry is an imperative pathway to pursuing the aim of high-fidelity HMI.

Keywords: Human-Machine Interaction (HMI), Flexible Electronics, Bio-inspired Sensors, Crack-based Structure, Mechanotransduction

1. Introduction

In the last fifty years, robotics has concentrated more on motion control and the high-level accuracy positioning of the end-effectors. But with the growing applications of collaborative robots in unstructured spaces, e.g., remote surgery and home services, the fundamental issue of HMI has changed to persistently comprehending the purpose of the human user through subtle mechanical indications [1]. In order to gather such subtle signals, the conventional engineering methods tend to fall short, and a transition to bio-inspired solutions may be sought. To create sensors that are even more sensitive than the human eye, one must have an understanding of the characteristics of biological sensing, namely, how the precision of mechanoreceptor networks makes human dexterity dependent [2]. This is a biological process that regulates the movement of ions by deforming structures, such as the case of the Piezo ion channels [3]. It provides a high signal-to-noise ratio and response in milliseconds, worth of response rendering it a basic blueprint of designs of flexible sensors in which charge carrier flux is regulated by micro-geometric variations to create signal amplification.

In spite of such developments, the existing sensing technologies have serious physical constraints in HMI applications. Rigid potentiometers do not have the compliance needed, and optical motion capture is limited by the line of sight requirement. Material physics gives a so-called sensitivity-stretchability trade-off, though flexible electronics are meant to solve these problems [4]. Highly sensitive materials normally have low fracture strain, and stretchable percolation theory-based nanocomposites are typically low sensitivity [5]. One way of avoiding this paradox is breaking it, which is a necessary condition to record high-fidelity HMI of micron-level isometric muscle contractions. Moreover, surface electromyography (sEMG) is popular, but it is often plagued with poor signal-to-noise ratios related to electromagnetic noise in the environment and variation in contact impedance [6].

This is a review of bio-inspired micro-crack technology as a potential hardware solution to the sensitivity bottleneck. It logically investigates the mechanical pre-processing principles that can be found in nature, including the amplification of the stress mechanism of arthropod exoskeletons. These principles are then described as being engineered by deposition of hard metal films on the flexible polymer substrates to cause microcrack arrays. The Disconnect-Connect model and quantum tunneling effects that cause the mechanisms of electronic transport are then outlined to provide the physical origin of ultra-high sensitivity. Lastly, the paper compares the comparative merits of using this technology with conventional bi-potential techniques of bio-potential in real-time robotic-controlled situations.

2. Bio-inspired micro-crack technology: concepts and practice

The section in question evaluates the arthropod-inspired micro-crack sensor technology, which is an enhancement of addressing the sensitivity bottleneck.

2.1. Nature as an educator: "hard-soft" mechanical amplification

Sensory abilities are often enhanced by the technology of the exoskeleton sensors, and the animals that deal with the predator have sensory qualities that outmatch artificial equipment. As an example, the desert scorpion uses the basitarsal compound slit sensilla (BCSS) to sense weak Rayleigh waves. This structure is anatomically distinct, with a heterostructure of hard-soft slits through the rigid exoskeleton filled in by a low-modulus flexible membrane. As a result of the large variations in the moduli, the mechanical stress is focused on the flexible membrane, making the micro-scale movement a hundred-thousand times greater to cause submembrane neurons [7].

On the same note, the cricket mechanism used by the piano gauges of hunting spiders filters under high-frequency prey information and rejects artifacts of low-frequency movement using a crack closure mechanism and viscoelastic pads [8]. The main benefit of these bio-inspired designs is that they can perform mechanical computing on the hardware level, including spectral analysis and noise filtering. The hardware level of computation is much less burdensome to central processing units than computation at the software level. One of the problems in making copies of these biological systems is, however, the challenge of making high-fidelity 3-dimensional micro-geometries. Although the biological structure is very selective, synthetic approximations can be afflicted by directional ambiguity or structural fatigue due to repeated loading.

2.2. Disconnect-connect model of electronic transport mechanism

Hard metal films are deposited on flexed polymer substrates to generate desired arrays of microcracks in order to replicate high sensitivity in biological systems in engineering. The Disconnect-Connect model explains the working principle of the sensors, which converts biomechanics to an electronic transport property. Indicatively, a study on spider-inspired sensors has empirically confirmed this model in which nanoscale changes in the crack are directly related to changes in resistance [2]. In the first state, the residual compressive stress positioning makes sure that the edges of the cracks are held in a closely interlocked manner to produce micro-contact of current flow. The flexible substrate drives the metal islands apart and decreases the contact area upon the introduction of minute tensile strain ($< 0.1\%$). Most importantly, the width of the crack grows but enters the nanoscale (less than 5-10 nm), thus electron transmission is through the quantum tunneling effect. Tunneling resistance is exponentially dependent on crack width ($R = 2$) and therefore, any minuscule geometry variations cause tunneling resistance to jump exponentially and produce Gauge Factors (GF) numbers in the thousands [8]. In the presence of no stress, the viscoelastic substrate supports the quick recoil and the reclosing of the edges of cracks to regain conductivity.

The approach is brilliant in bypassing the flaws of the conventional piezoresistive materials since the stress singularity at the tip of the cracks is exploited to provide an ultra-high sensitivity. However, the dependence of the cracks on the nanoscale may create some stability problems. The viscoelastic recovery of the substrate is very crucial to the sensor's workings; therefore, there will be hysteresis and signal drift in the course of high-frequency dynamic cycling in case the input frequency is not equal to the relaxation time of the material.

2.3. Structural design: the structural design has diversified over time

Outside the core solution of crack structure, several biomimetic versions have been generated to meet the multidimensional sensors of robotic manipulation. The type of structure in the micro-pyramid interlocking form that resembles the type of epidermal-dermal linkage of the human skin promotes sensitivity to normal pressure whilst reducing the interference of the forces of lateral directions, and it is best in fingertip tactile sensing [5]. The other important evolution is the hierarchical crack design that is based on tree bark cracks, in which the large cracks handle the wide range of strain, and the small cracks detect the small stimuli to balance both the range of dynamics and the sensitivity. Also, it has been suggested that fold-crack hybrid structures that resemble accordion bellows could serve to buffer the stress by means of flattening effects and that they would neither experience a total conductive failure during high deformations of a joint [4,9,10].

These structural developments illustrate the flexibility of the crack-based technology when it comes to making modifications to meet particular HMI requirements, such as the sensitive acquisition of texture to the massive tracking of motion over extensive distances. Nevertheless, the enhanced complexity of the structure presents a challenge to mass production, which is typical. It is still challenging to ensure the consistency of arrays of random crack patterns or multifaceted folded patterns across large region sensors, potentially causing the sensor-to-sensor variation, and the exposure of variation requires an application-specific calibration and stabilisation of a sensor array.

3. Technological benefits and opportunities

Although the current technology of intelligent prosthetic control is based on surface electromyography (sEMG), bio-inspired deformation sensing technology has been demonstrated to have considerable engineering merits, especially in terms of signal strength and de-noising levels.

First, the signal source strength is stronger sEMG captures bioelectrical signals of microvolts, which are very vulnerable to the surrounding electromagnetic interference and signal drift due to the effect of sweating on the electric field. By comparison, biomimetic deformation sensors generate high-level physical signals at voltages, with a signal-to-noise ratio often 3-6 orders of magnitude better than sEMG [4]. In addition, the advanced technologies of the packaging can enable such sensors to have consistent functionality in such challenging conditions to efficiently eliminate the effects of moisture and dust.

Second, the decoding mapping is simpler and less efficient. The interaction between sEMG signals and limb movements is also usually nonlinear and complex in nature and may require deep neural networks with a high power of computation which imposes system latency. On the other hand, deformation sensors directly provide geometric stretching of skin surfaces which has a quasi-linear dependence on the bending angles of joints. High-precision position estimation of the intuitive physical mapping is possible with simple linear regression response time of as low as 10 ms, which is much lower than the computational cost of real-time closed-loop control [7].

Nevertheless, even with these benefits, there are existing technological drawbacks with crack-based sensors. The hysteresis and signal drift due to the dependence of the viscoelastic recovery of polymer substrates may happen during high-frequency dynamic cycling, which may influence long-term repeatability. Also, achieving uniformity in the manufacturing of random configurations of crack arrays in massive expanses is a major issue for standardized mass production.

The way forward should be based on dealing with these problems. The decoupling of multimodal stimulus like the ability to distinguish between strain and temperature variations, as well as counteracting intrinsic viscoelastic hysteresis, will require sensor integration with complex machine learning algorithms. Moreover, enhancing technology in fabrications to make materials stable will be of great essence, as far as the business is concerned.

4. Conclusion

Concisely, the biomimetic microcrack technology has achieved a breakthrough to the hard-soft myth in that it is able to mimic the hard-soft stress concentration mechanism in biology to solve the sensitivity-stretchability paradox of traditional materials. This technique is used to produce ultra-high sensitivity and high response times by intelligently employing mechanical singularity and the quantum tunneling phenomenon at the crack tip. Structural bio-mimicry is a stronger and less latent solution than traditional bio-potential solutions.

In order to allow commercial viability, future research will have to overcome the challenges of producing uniformity and material fatigue in the process of extensive dynamic cycling. It is also important that these sensors are fused with a multidimensional machine learning; that fusion is necessary to separate multimodal stimuli, e.g., to distinguish between strain and thermal variation, and to correct natural viscoelastic hysteresis. Eventually, systemic bio-fabrication and intelligent signal processing will be synthesized, and the autonomous electronic skin will be developed, realizing the idea of really anthropomorphic robotic perception into reality.

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