THE DESIGN OF TACTILE SENSORS AND THEIR ELASTIC COVER

Theses of the Ph.D. dissertation

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PÁZMÁNY PÉTER KATOLIKUS EGYETEM
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1. Introduction

Touch is a fundamental and intriguing sensory modality that is also the least known from many points of view. It is fundamental because tactile information is truly indispensable for our everyday life. Intriguing because it is the only modality that maps the environment through its “tangible” physical reality on the whole body, without having the sensory receptors located in a specific organ. Most of the other modalities sense the world remotely, through secondary physical substances emitted by the observed distant objects. Vision requires scattered light, hearing makes use of the reflected or generated auditory waves, olfaction calls for molecules traveling in the air. In contrast, tactile sensation through concrete physical contact informs us unquestionably about the surroundings. If we see a mirage but we cannot touch it, we know that it is not there. Conversely, if we bump into a glass door, we will notice it for sure, even if we could not perceive it visually. In other words, in case of controversial information coming from more modalities at once, tactile sensation will be the dominant one in many cases.

In general, tactile modality is a truly important sensory system of ours that once being investigated or modeled scientifically, reveals deep beauty and brings on fascination. My Ph.D. work also concerns the sense of touch, but in place of the biological systems it builds on artificial tactile sensors.

The heart of my research is a tactile-sensor array developed at the Institute for Technical Physics and Materials Science of the Hungarian Academy of Sciences (MTA MFA). This tiny MEMS (Micro-Electro-Mechanical-Systems) device encloses sensory and signal-processing elements. It is novel in the manner that compared to the commercially-available pressure-sensor arrays, it can measure, process and pass on not one, but three components of the surface load, namely, not only the one perpendicular to the surface but the two shear components as well. During my work I participated in the development, experimentation and system-level integration of these devices, but in my research I mainly focused on the examination and design of the skin-like elastic cover of the sensors.

The elastic cover is an indispensable key component of the tactile sensors. Besides providing a certain amount of physical protection, it also plays a fundamental role in the overall procedure of sensation, as a mechanical information-coding layer between the sensors and the environment (let us just think about the increased tactile sensitivity around an abrasion, or our thickening sole during the summer holidays). The elastic layer transfers the surface forces to the sensors in the form of distributed mechanical stress/strain/deformation, no matter which system—mechanoreceptors in the deep skin or artificial tactile sensors—receive them. Consequently, the *elastic cover* can be treated as the *first spatial-temporal, dynamic information-coding layer* of the sensory structure.

My first task was to model and understand this non-trivial, spatial-temporal coding mechanism. In the second run I used an inverse approach—I investigated how I could determine the surface load distribution from the measured, coded signals by making use of the coding mechanism or, alternatively, by intentionally *designing* the geometry and physical parameters of the elastic layer using neuromorphic features in the sensor design.

2. Methods of investigation

Before working with artificial tactile sensors, it is worth to get acquainted with one of Nature's many masterpieces, the *human* (or any other living organism's) *tactile system*. All components of an artificial tactile sensor can be associated with parts of the biological analogue; therefore, for a neuromorphic design we can obtain many great ideas from the big old evolution that started its development millions of years ago. It is simply unwise to start working with tactile sensors without gaining knowledge about the neurobiology of touch, the function of the mechanoreceptors or the anatomical structure or mechanical behavior of the skin.

The sensing paradigm of the MEMS devices used in my work is the *piezoresistive effect*. When a piezoresistive material is exposed to mechanical load, it changes its resistivity proportionally to the strain in the material. Our sensors include deformable micro-bridges that contain embedded piezoresistors. Therefore, for the design and evaluation of the sensors we certainly need some knowledge about the MEMS technology in general and the piezoresistive effect in particular.

Continuum-mechanics is the key word for the mathematical description of the elastic cover of the sensors. In the first run, the elastic matter can be treated as a homogeneous, isotropic, infinite *half-space* that obeys Hooke's law. The input forces act on the only open surface of the half-space, and create a complex stress profile inside the material. Since the stress is mostly concentrated around the indentation and decays rapidly with distance, we can fairly approximate the behavior of the real, finite rubber with the infinite half-space at a depth corresponding to the real rubber thickness. The first task is now to solve the equilibrium equations of the rubber for a given surface-indentation profile, and find the stress/strain/deformation distribution at that specific depth. The inverse problem is about the regeneration of the surface indentation profile from discrete number of strain measurements under the rubber.

The first solutions to the direct problem of the elastic half-space were found a long time ago, around the end of the nineteenth century; yet, the elastic theory had nothing to do with tactile sensors then. It was only in the mid-eighties of the last century when the model became the primary mathematical description of the skin and the artificial cover of pressure sensors, however, with three degree-of-freedom sensors in view, the theory still calls for enhancement.

One of my results is that as an analogue to the finger ridges, I changed the surface of the flat cover to a certain, defined shape. Consequently, the half-space model could not be used any more in the original form. Therefore, as an extension of the elastic half-space, I made a *finite-element model* in contribution with Balázs Fodor to be able to describe the cover with the new geometry as well.

The sensors of the MTA MFA were tested and developed with a *special experimental setup.* In the measurement system the sensors are fixed to a table that can be tilted and moved subtly with a high-precision stepper motor. The sensors can be loaded with forces of different angle and amplitude, acting on a single point or a bigger area. The signals go through an amplification stage developed at our lab and are finally transferred to a computer equipped with special evaluation software.

3. New scientific results

Thesis I: Qualification of tactile sensors and their elastic cover

To work with tactile sensors efficiently and reliably, we need to be familiar with their performance. First, we need to compare their theoretical response with the measured one, without a cover. Second, we need to characterize our sensors again in the presence of the simplest, flat elastic covers. Finally, we have to support the applicability of the elastic model describing the behavior of the cover, with measurements both in the direct and the inverse approaches.

I.1. I worked out the exact physical model of the MEMS suspended-bridge type, piezoresistive, three-axial tactile device of the MFA, and verified this model and the preliminary finite-element simulations with characterizing experiments on a new, complex measurement setup.

Using the literature, I adjusted the theoretical description of the sensors to describe precisely the bulk micromachined tactile device of the MFA. The linear characteristics of the model and the sensitivity of the sensors predicted by the preliminary finite-element simulations are in accordance with the real measurements performed on the complex experimental setup.

I.2. Establishing high spatial-resolution, three-axial measurements, I verified that the infinite elastic half-space

model describes the behavior of the finite, flat elastic cover well. Relying upon my experimental results, I confirmed that the signals of the covered sensors are proportional to three components of the local strain tensor of the cover.

Using a flat elastic cover, the receptive field of a sensor turns into a spatially-continuous, extended region, where the sensitivity of the device is highly inhomogeneous, as described by the material's model. I measured this three-component receptive field distribution with a spatial resolution of 3 μm over the total sensitive area of one single sensory element. I compared the measured distribution with the one predicted by the half-space model and confirmed that the measured signals are proportional to the strain-tensor components, even though it was assumed before that they represent the stress tensor.

I.3. I solved the inverse problem of the elastic half-space for an arbitrary point load, and using the results, I established tactile hyper-accuracy on sensors with a flat cover.

Using the known coding mechanism of the flat elastic cover, I found a solution to determine the exact location, direction and amplitude of an arbitrary point load over the cover surface. I utilized my theoretical results on the sensors and in the meantime verified them with measurements: using the three signals of one single element of a tactile array, I calculated the location of a normal point load on a receptive field size of 300×300 μm with 3 μm (1%) accuracy. I also determined the amplitude of the load reliably. I integrated the solution into the software environment resulting in a real-time algorithm.

Thesis II: Neuromorphic elements in the tactile-sensor design

The surface of the high-resolution tactile systems of nature is not flat in most of the cases. Instead, it is usually equipped with fingerprints, different kinds of grooves or hair. Thoroughly investigating the role of these characteristics in biological systems, I could introduce new aspects into the artificial sensor design. Using the fingerprints as a model, I changed the geometry of the previously used flat surface to alter several properties, the sensitivity and the general coding mechanism of the cover on purpose. The most important new results are the following:

II.1. Introducing hair- and fingerprint-like elements into the sensor design, I changed the sensors overall characteristics, increased their sensitivity and experimentally verified the role we believe these elements have in biological systems.

Since the complex coding mechanism of the flat elastic cover makes signal processing quite problematic, I designed non-flat covers with specific neuromorphic shape and structure. In addition to successfully improving the characteristics of the sensors and increasing their shear-sensitivity, I also validated the hypotheses that fingerprints are crucial signal-coding and amplifying structures, while hairs are fundamental in shear-load sensing.

II.2. Using finite-element simulation results, I proved that by consciously designing the geometry of the cover, its coding mechanism can be simplified efficiently. Applying elastic hemispheres on the cover surface, I provided a method for localizing the input load and for measuring the three force components directly and independently under the cover.

I verified my theoretical results on the three-axial sensors through a texture-classification example. Using the hemispheres, on the one hand, I maintained the physical protection of the cover; on the other hand, I localized the originally continuous input and thus avoided the inverse-calculation problems originally coming from the complex coding mechanism of the material.

II.3. Using elastic hemispheres on an arbitrary pressure-sensor array, I developed a design plan for a special cover, which enables the extraction of independent shear-load components from the originally one-axial sensors.

The elastic hemispheres can be applied successfully on simple one-axial pressure-sensor arrays as well. In this case one hemisphere covers four one-axial elements of the sensor array. Combining these four signals I gained shear-load information effectively—based on the finite-element simulation results again. The method can be used generally on an arbitrary pressure-sensor array, with any size or element number. I verified my theoretical assumptions with measurements on a 9×9 element capacitive array.

4. Application of the results

The applicability of my results obviously goes along with that of tactile sensors. Their most "handy" function is in an arbitrary grip task on robotic arms. In addition to the industrial use and scientific research aims, nowadays a more and more active market is opening in the medical research field. We can utilize our sensors on endoscopes where manual touch is unattainable. Combining the sensors with a proper haptic display we can construct a system that helps in virtual tele-operation projects. In the long run the sensors could be used as a substitute for the mechanoreceptors on the arm prostheses of amputees.

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