Tactile sensing arrays – design and processing

GÁBOR VÁSÁRHELYI, MÁRIA ÁDÁM, CSABA DÜCSŐ, ISTVÁN BÁRSONY

Research Institute for Technical Physics and Materials Science, Hungarian Academy of Sciences
{vasarhelyi, adam, ducso, barsony}@mfa.kfki.hu

ATTILA KIS

Péter Pázmány Catholic University, Faculty of Information Technology
kis@itk.ppke.hu

Reviewed

Keywords: tactile sensor, elastic cover, MEMS, three-axial force sensing

Tactile sensors are commonly used in industrial, medical or virtual-reality applications, but the majority of commercial tactile systems are capable to detect pressure maps only. In this article we present a novel tactile sensing array that processes all three components (normal and shear) of the tactile information at every sensory element (taxel – tactile pixel). We describe the processing technology of the integrated micro-sensors, write about the information coding behaviour of its elastic cover and, finally, we show a robotic application example, where the three-component force measurements play a fundamental role.

1.Introduction

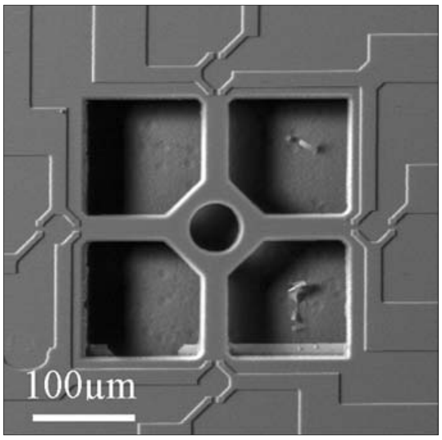
Tactile sensing is probably the second most important, most complex perception of the human body after the vision. The human skin is filled with tiny mechanoreceptors that separate different components of tactile input (static pressure, motion, vibration, etc.) into parallel channels, and send them to the central processing unit, the brain.

Our final goal is to mimic the operation of this sensing-processing system with artificial tactile sensors that could be integrated into robotic hands, medical diagnostic devices or even into e.g. arm prostheses to improve their efficiency.

The core element of our research is a three-axial force sensing array, developed by the Research Institute for Technical Physics and Materials Science (MFA). This tiny MEMS (Micro-Electro-Mechanical System) device is a single-crystalline Si-based sensor that – unlike the commercial tactile sensory arrays – measures and processes not only the normal, but also shear components of the force vectors at its surface.

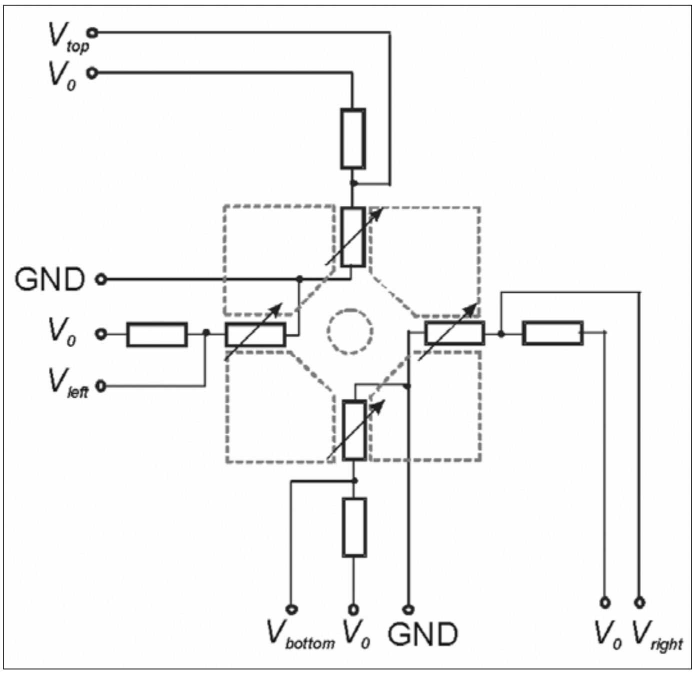
The elastic cover is an indispensable key component of the tactile sensors. Besides offering a certain amount of physical protection, it also plays a fundamental role in the overall procedure of sensation as a mechanical information-coding layer between the sensors and the environment (let us just think about the increased tactile sensitivity around an abrasion, or our thickening sole during summer holidays). The elastic cover can be treated as the *first spatial-temporal, dynamic information-coding layer* of the sensory structure, therefore, its behaviour must be taken into account throughout the design of every tactile device. Our goal is on the one hand

Figure 1.



SEM view of a piezoresistive sensing element (taxel).
Characteristic dimensions:
suspension beams: 80x32x10 µm³,
central reinforced membrane: 100x100x10 µm³,
hole diameter: 50 µm,
cavity etch depth: ~35 µm.
The piezoresistor pairs (deforming and non-stressed reference) are symmetrically formed around the joints of each beam.

Figure 2.



The layout of a taxel indicating the placement and the circuit connection of the four piezoresistor pairs.

to better understand human tactile sensing. On the other hand, we would like to copy ideas from nature to improve the quality of our artificial heptic sensory devices.

The general description of our system is followed by an application example through a *proactive robotic grasping task*.

This article is the English version of a review in Hungarian review that summarizes our previous international publications listed in the references [1-7].

2. Sensors by MEMS technology

The monolithic tactile sensor arrays are formed in single-crystalline Si (c-Si) by the well-known IC processing technology complemented with an appropriate bulk micromachining technique in order to form the 3D deforming structure. The extraordinary mechanical properties of single crystalline Si combined with the above fabrication techniques enable us to produce intelligent smart sensors of various functions.

All the tactile elements (taxels) of the sensor array are suspended, perforated c-Si membranes with perfectly positioned, embedded piezoresistors *(Fig.1)*. The change of the resistance of each piezoresistor is proportional to the emerging stress in the deforming membrane during loading.

Single-side porous Si bulk micromachining technique was used for releasing the n-type c-Si membranes. The location and direction of the ion-implanted p+ piezoresistors was determined by finite element model calculations in order to select the most sensitive area, i.e. where the load-generated mechanical stress reaches its maximum.

All the piezoresistors are coupled with a serially connected non-deforming reference element placed in the Si bulk maintaining constant resistance even when loading the taxel. The two resistors form a simple voltage divider or a half Wheatstone bridge, therefore, the readout is an analogue DC signal which is proportional to the generated mechanical stress *(Fig. 2)*.

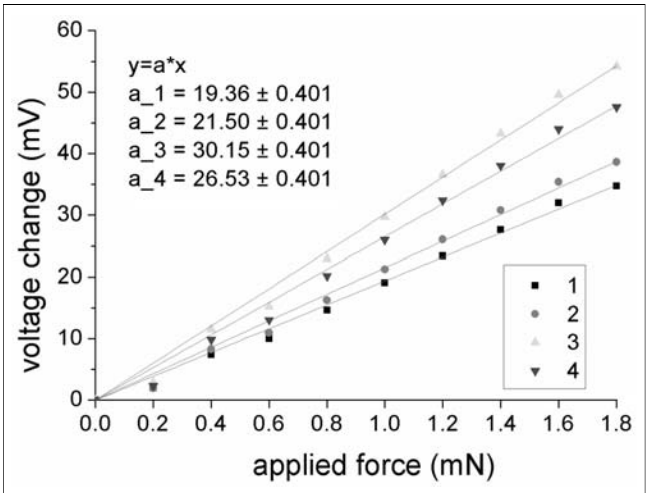
All the taxels consist of four independent piezoresistor pairs in order to resolve the vectorial components of the attacking force. The linear relationship between the voltage changes and the attacking force in the centre of the sensor element can be described by the following equations:

$$F_x = \frac{1}{V_0 \alpha_{ls} \pi_{44}} \left(\Delta V_{right} - \Delta V_{left} \right),$$
$$F_y = \frac{1}{V_0 \alpha_{ls} \pi_{44}} \left(\Delta V_{top} - \Delta V_{bottom} \right), \qquad (1)$$
$$F_z = \frac{1}{V_0 \alpha_{ln} \pi_{44}} \frac{\left(\Delta V_{left} + \Delta V_{right} + \Delta V_{top} + \Delta V_{bottom} \right)}{2}$$

where F_i are the three components of the attacking force (*z:* normal, *x* and *y:* tangential) V_0 is the common voltage, ΔV is the measured voltage change, π_{44} is the dominant piezoresistive coefficient, α_{ln} and α_{ls} are the linear normal and shear coefficients in the given geometric arrangement.

The measured sensitivity and the linear characteristics of the sensors correspond well to the preliminary finite element model calculations (4-6 mV/mN/V) *(Fig. 3)*.

Figure 3.



Linear responses of the four sensing elements exposed to normal load. The sensitivity difference is due to the geometric mispositioning of the attacking needle of the test device.

3. Integrated sensor arrays

Real tactile applications often require sensor arrays of different size and density. Therefore, two array chips were developed. A four element array (2x2) can easily be formed with simple multiplication of the taxels *(Fig. 4)*.

When aiming at further increasing the number of taxels, one faces the contact wiring problem. The large number of wires requires considerable floor space, multilevel metallization and an equal number of bonding pads, which further complicates the inherently critical assembling process.

The metallization problem of large arrays can easily be circumvented by integrating decoders or multiplex-

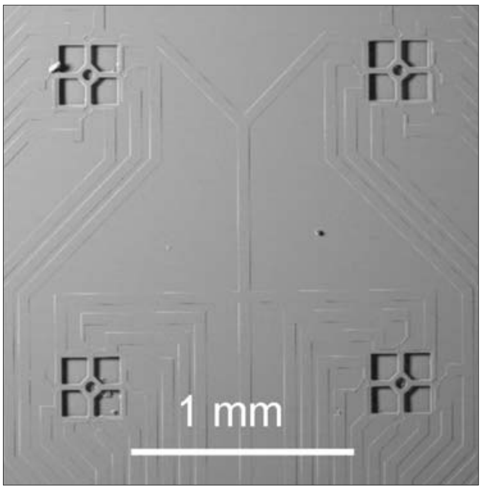


Figure 4. A 2x2 element sensor array. Taxel-size: 0.3x0.3 mm² Spacing: 1.5 mm

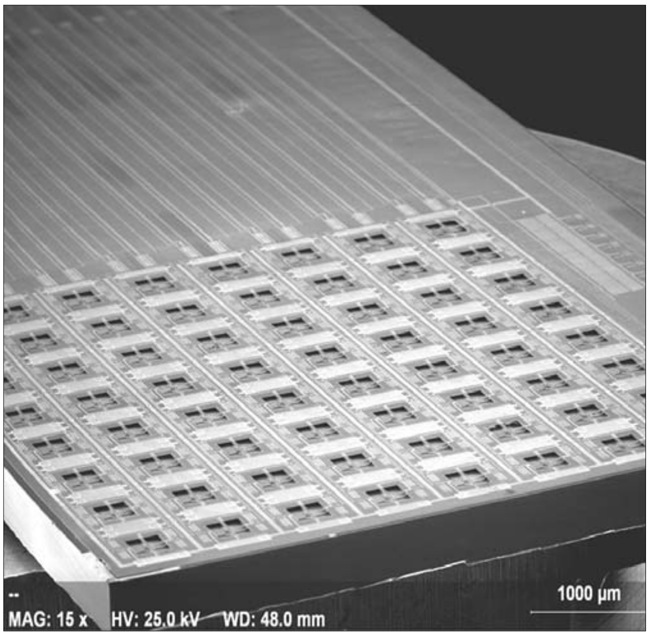


Figure 5.
The 8x8 element tactile sensor array fabricated with CMOS compatible micromachining processes (patent pending)

ers in conventional chips. Nevertheless, in most of MEMS sequences the 3D micromachining as well as the fragile suspended membranes formed make the integration of the required circuitry quite difficult.

Therefore, we developed a proprietary CMOS compatible process sequence, which enables the integration of driver circuitry with porous Si micromachined sensors. Using this patented process we fabricated an 8x8 element tactile sensor chip with on-chip current generators and decoders *(Fig. 5)*.

4. Effects of the elastic cover

As mentioned in the introduction, the elastic cover is an indispensable and fundamental part of every tactile sensor or organ. The elastic layer transfers the surface forces to the sensors in the form of distributed mechanical stress/strain/deformation, no matter which system receives them – mechanoreceptors in the deep skin or artificial tactile sensors – receives them.

Continuum-mechanics is the key word for the mathematical description of the elastic cover of the sensors. In the first run, the elastic material can be treated as a homogeneous, isotropic, infinite *half-space* that obeys Hooke's law. The input forces act only on the open surface of the half-space, and create a complex stress profile inside the elastomer. 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 elastomer thickness.

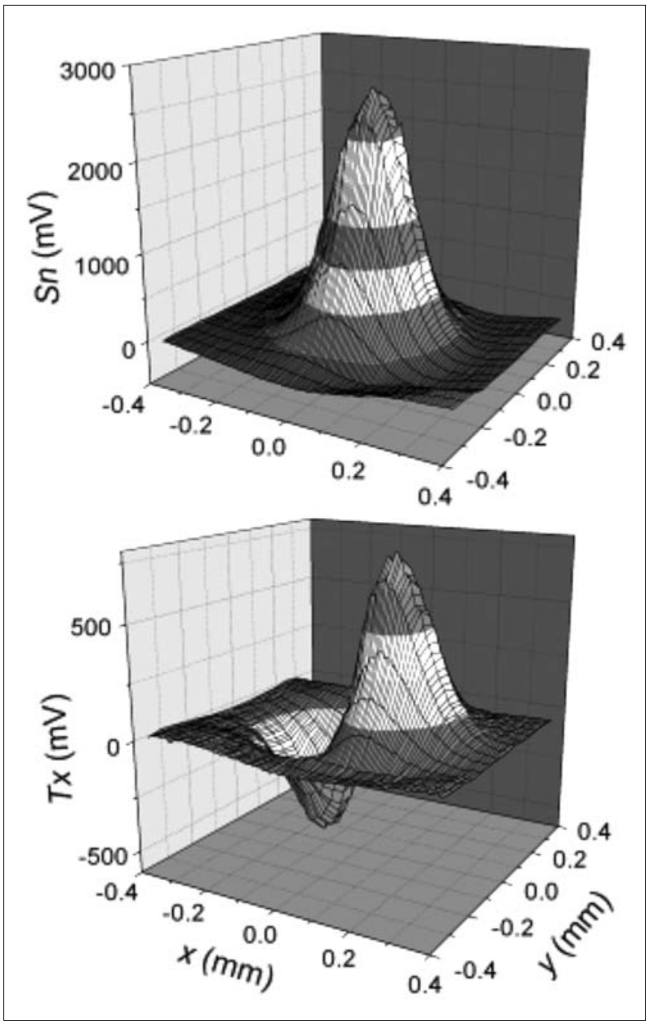
The first task is to solve the equilibrium equations of the rubber for a given surface-indentation profile, and to find the stress/strain/deformation distribution at that specific depth *(Fig. 6)*. A much more important practical task is the solution of the inverse problem, i.e. the reconstruction of the surface indentation profile from discrete number of strain measurements under the rubber.

Although first solutions to the direct problem of the elastic half-space were elaborated long time ago, towards the end of the 19th century; by that time the elastic theory had nothing to do with tactile sensors. 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. With the appearance of three degree-of-freedom tactile sensors, the theory called for enhancements again.

One of our results is that we changed the flat surface of the cover to a certain, defined shape, mimicking the human skin with finger ridges or other sophisticated tactile organs developed by the evolution *(Fig. 7)*.

Consequently, the half-space model could not be used any more in the original form. Therefore, as an extension of the elastic half-space, we created a *finite-element model* to describe the mechanical behaviour of the cover.

Figure 6.
Two components of the stress profile inside the elastic cover at a given depth, generated by the simplest point load on the surface. The measurement results correlate well with the theoretical predictions.



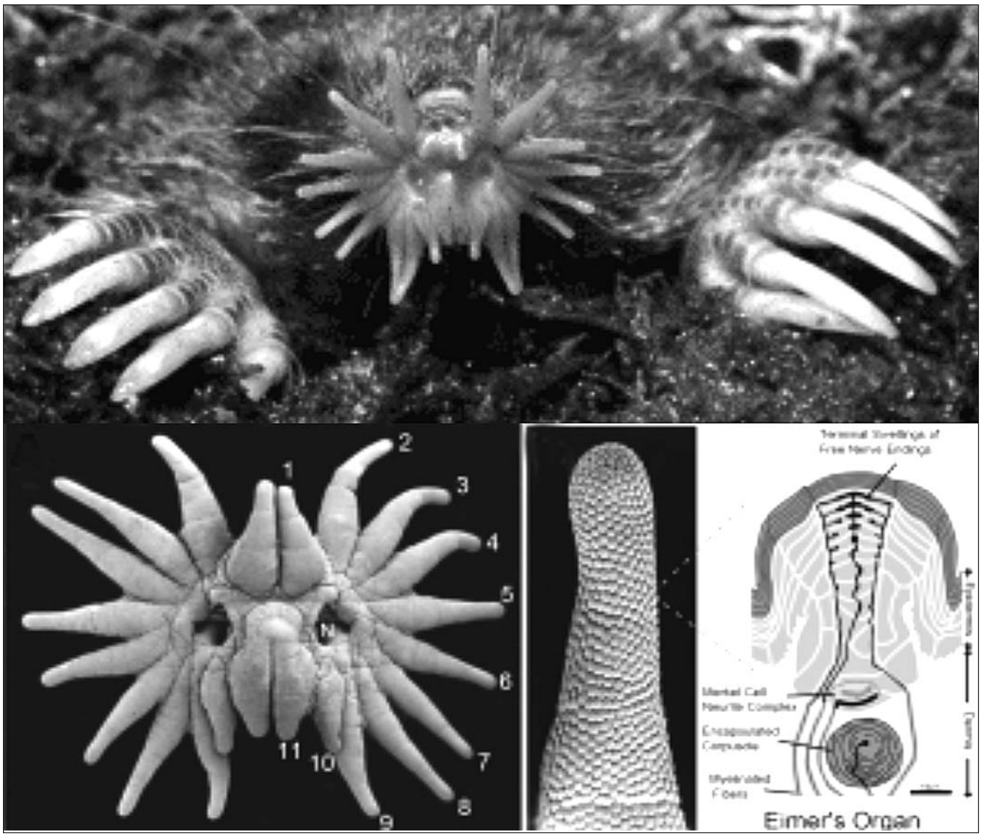


Figure 7.
The world's most developed tactile organ of the star-nosed mole (Condylura cristata), consisting of elastic hemispheres for mechanically filtering and amplifying the tactile signals.

The neuromorphic cover „stolen" from the star-nosed mole basically consists of elastic hemispheres over the cover surface with the following intriguing properties:

– The hemispheres convert the spatially-continuous input force distribution into a discrete one by localizing the forces to their tip.

Figure 8.
Finite-element model of the elastic hemispheres under loads with different directions (above). The linear and independent stress components arising at the location of the sensors (below).

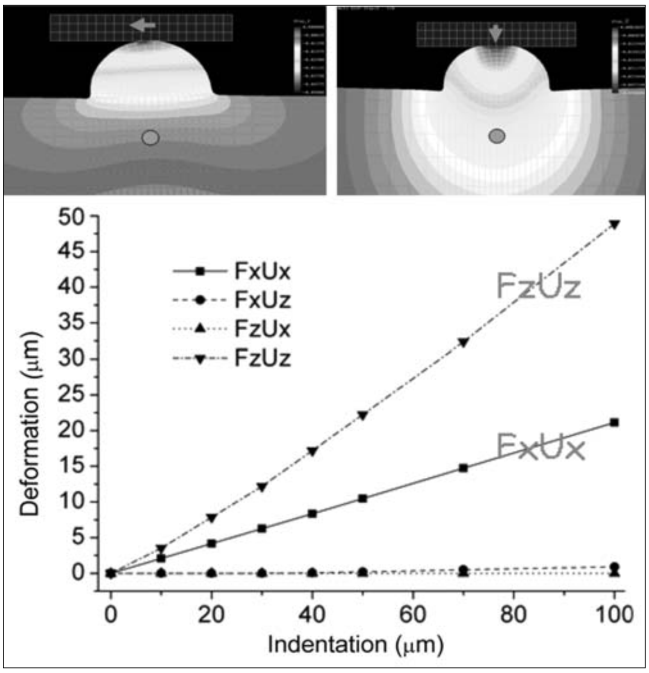
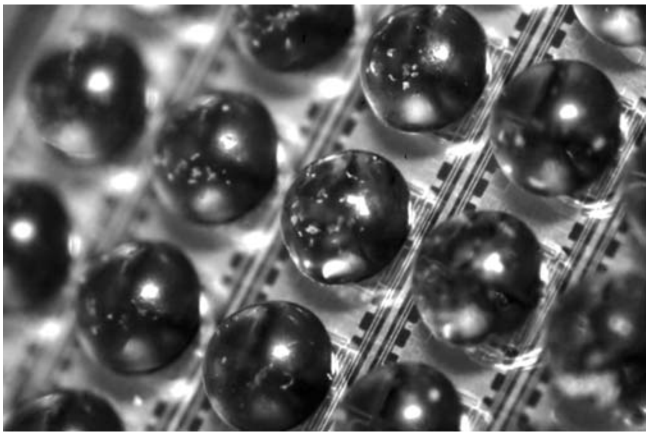


Figure 9.
8x8 sized sensor array with elastic silicone hemispheres on top



– The hemispheric structure modifies the information coding behaviour of the whole cover in such a way that the three components of the local input forces can be measured linearly and independently with sensors located under the structure *(Fig. 8)*.

We equipped the sensor arrays with geometric elastic covers designed according to the finite-element simulations *(Fig. 9)*, and improved thereby the shear sensitivity of the system. We could also verify experimentally the role of these geometric mechanical structures in biological systems.

5. The tactile system

The signals are pre-processed and transferred to a PC by a read-out circuitry. This read-out board filters and amplifies the analog signals and also calibrates the sen-

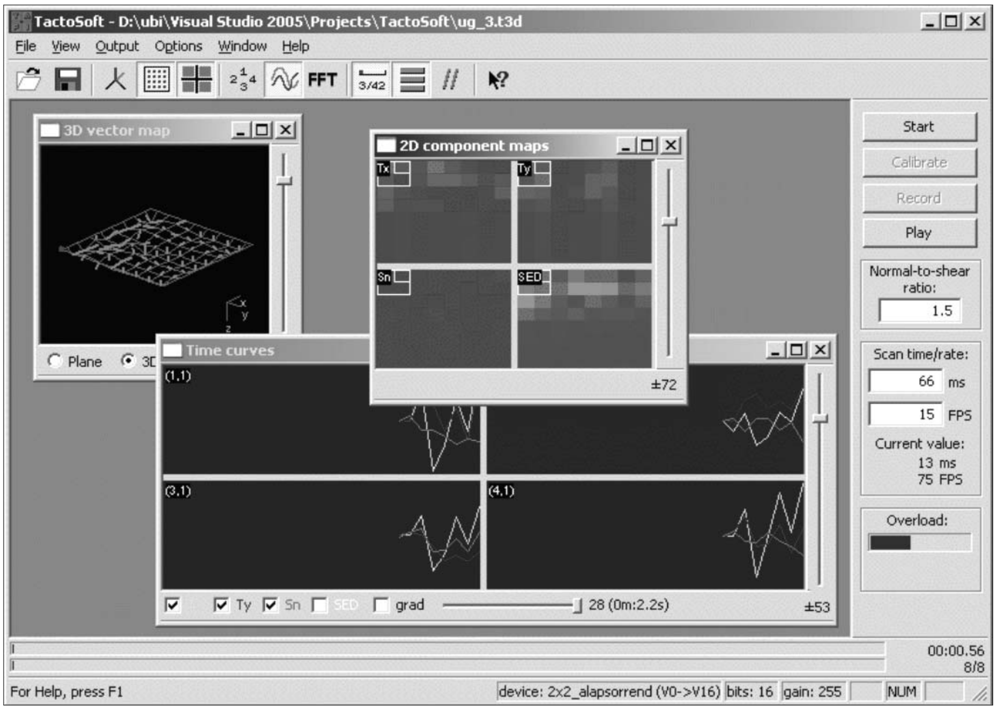


Figure 10.
The graphical user interface of the tactile software

sor array. After A/D conversion the signals are sent to the PC through RS232 or USB communication line.

The data are stored, processed (on-line or off-line) by PCs running under WinXP, by a software developed for analyzing tactile events *(Fig. 10)*.

6. Proactive-adaptive robotic arm control-slippage detection

In order to illustrate the use of the three axial tactile sensors, an experimental system was constructed. The main component of the system is a two fingered robotic arm that can hold small and medium sized objects *(Fig. 11)*.

For handling fragile or slippery objects with unknown parameters, a continuous tactile feedback is indispensable in order to prevent slippage. Let us consider the case when a two-fingered robotic arm holds an empty glass and we start to fill it with water: the glass changes its weight with time. In that case the grasping force has to be adapted, too, proportionally to the increasing weight of the object. If the holding force is too small, the object can slip out of the fingers. This must be detected by the system in due time to give an adequate response and prevent slippage, namely, to increase the grasping forces.

A great advantage of three-axial tactile sensors is the capability of measuring shear forces. Thereby knowing the slippage threshold, the robot's control can be alerted before the actual slip, preventing any relative motion between the object and the robot fingers *(Fig. 12)*.

Figure 11.
The two-fingered Katana robot grasping an object between the fingertips equipped with tactile sensors

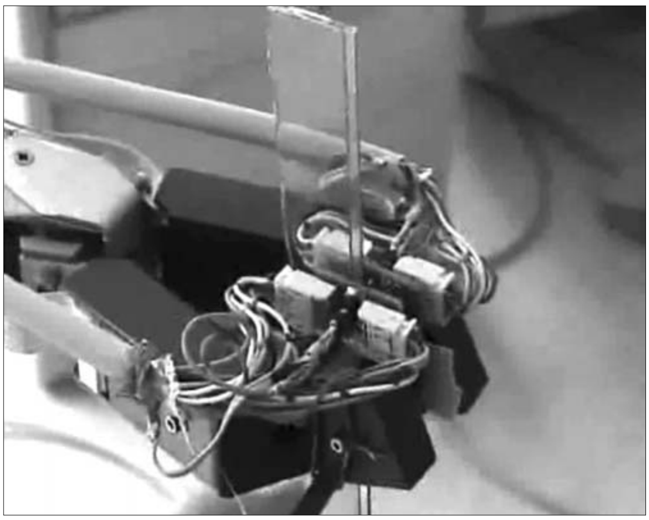
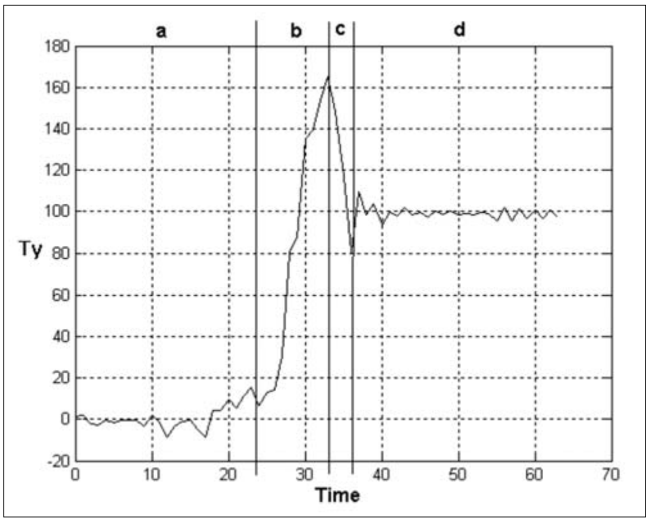


Figure 12.
The time evolution of 3D grasping through tactile forces: a) nothing is grasped; b) shear force increasing proportionally to the growing weight; c) object starts to slip out, force decreases; d) constant motion with constant force determined by the kinetic friction coefficient.



6. Summary, applications

An introductory overview to the design and processing issues of integrated tactile sensor arrays was presented. The main achievement of the novel system is the capability of 3D resolution of the attacking force in every taxel. Since shear forces appear in every grasping task, the capability of three-axial measurements is a must in tactile sensing.

In order to exploit the results presented here in a nutshell, and to expand our capabilities, MFA, PPKE and RG Co. established a spin-off company, TactoLogic Ltd., Budapest. Besides commercializing complex systems dedicated for education and research purposes, the company is going to introduce the tactile devices in medical application. Endoscopes, catheters, autonomous microrobots equipped with three-axial taxels could provide tactile information from remote places, where human hand could never touch before. Moreover, accurate physical diagnostics can also be targeted in long term.

By integrating this system with tactile displays, tactile tele-sensing will also be achievable. In the long run, tactile sensors could be also exploited in any prosthetic device.

Acknowledgements

This tactile research was initiated by the TELESENSE project (NKFP 035/02/2001) of the Széchenyi Program. Part of the work was supported by OTKA via T047002 project.

References

[1] G. Vásárhelyi, M. Ádám, É. Vázsonyi, Zs. Vízváry, A. Kis, I. Bársony, Cs. Dücső, "Characterization of an Integrable Single-Crystalline 3D Tactile Sensor," IEEE Sensors Journal, August 2006, Vol. 6, No. 4, pp.928–934.

[2] G. Vásárhelyi, M. Ádám, É. Vázsonyi, I. Bársony, Cs. Dücső, "Effects of the Elastic Cover on Tactile-Sensor Arrays," Sens. Actuators A, 2006, Vol. 132, pp.245–251.

[3] G. Vásárhelyi, B. Fodor, T. Roska, "Tactile Sensing-Processing: Interface Cover Geometry & Inverse Elastic Problem," Sens. Actuators A, 2007, Vol. 140, pp.8–18.

[4] Zs. Vízváry, P. Fürjes, M. Ádám, Cs. Dücső, I. Bársony, "Mechanical Modelling of an Integrable 3D Force Sensor by Silicon Micromachining," National Institute for Research and Development in Microtechnologies (Bucharest) (ed.) Special issue featuring selected papers from the 13th European Micromechanics workshop (MME'02), Bristol, Institute of Physics Publishing, 2003, pp.165–168.

[5] É. Vázsonyi, M. Ádám, Cs. Dücső, Zs. Vízváry, A.L. Tóth, I. Bársony, "Three-dimensional Force Sensor by Novel Alkaline Etching Technique," Sens. Actuators A, Vol. 123-124, No. 23, Sep. 2005, pp.620–626.

[6] M. Ádám, T. Mohácsy, P. Jónás, Cs. Dücső, É. Vázsonyi, I. Bársony, "CMOS Integrated Tactile Sensor Array by Porous Si Bulk Micromachining", Sens. Actuators A, In Press, Corrected Proof available online 6 Aug. 2007.

[7] A. Kis, F. Kovács, P. Szolgay, "3D Tactile Sensor Array Processed by CNN-UM: A Fast Method for Detecting and Identifying Slippage and Twisting Motion," Int. Journal on Circuit Theory and Application (CTA), 2006, No. 34, pp.517–531.

Authors

Gábor Vásárhelyi received his M.Sc. degree in engineering-physics from the Technical University of Budapest, Hungary, in 2003, and his Ph.D. degree in technical sciences (infobionics) from the Péter Pázmány Catholic University, Faculty of Information Technology, Hungary, in 2007. He is currently a research fellow at the Institute for Technical Physics and Materials Sciences, and the chief technology officer of TactoLogic Ltd. His main research fields are connected to artificial tactile sensory systems.

Mária Ádám received the MSc degree in electrical engineering from the Technical University of Budapest, in 1973. She was R&D engineer at TUNGSRAM Ltd., at the Department of Semiconductors, from 1973 to 1982. From 1982-1985 she spent three years with the Microelectronics Co. Currently she is a research engineer at the MEMS Laboratory of the Research Institute for Technical Physics and Materials Science (MFA). Her research interests include design, development and processing of silicon-based mechanical and gas microsensor structures. She is co-author of about 25 scientific papers and one patent.

Csaba Dücső was born in Hungary, in 1959. He was graduated as a chemist in 1983 and received the Ph.D. degree in chemistry from the Eötvös Lóránd University, Budapest, Hungary. He was the head of the MEMS laboratory of MFA, Budapest between 1992 and 2007. His research interests include Si based MEMS with special emphasis on integrated gas and mechanical sensors as well as the development of related processing technology. At present he is in charge of R&D of thin film solar cells at BudaSolar Technologies Ltd., Budapest. He is co-author of over 70 papers published in periodicals or conference proceedings and holds 4 patents pending.

István Bársony graduated in electrical engineering from the Technical University of Ilmenau, Germany in 1971. He holds a C.Sc from the Hungarian Academy of Sciences (1978) and a PhD from the Technical University of Budapest (1996) and a D.Sc from the HAS (2001). During his professional career he was working on research assignments in Hungary mainly in silicon technology, in Japan (1983–1986) on imaging application of the Static Induction Transistor, in the Netherlands (1988–1993) at the MESA Research Institute of the University of Twente on Rapid Thermal Multi-Processing. Since 1993 he has been with the Research Institute for Technical Physics and Materials Science of the Hungarian Academy of Sciences, MFA Budapest, from 2004. He is the director of MFA. He has led several international projects a/o on solar cell and microsystems research. He holds 12 patents, published over 80 scientific papers and is a professor of nanotechnology at the University of Veszprém.

Attila Kis received his MSc degree in electrical engineering from the Technical University of Tirgu Mures, Romania, in 2001. From 2001 to 2002 he was co-researcher at the Computer and Automation Research Institute of the Hungarian Academy of Sciences, Analogical and Neural Computing Systems Laboratory. He received his PhD degree at Péter Pázmány Catholic University, Multidisciplinary Technical Sciences Doctoral School, Budapest, Hungary, in 2007. His research interests are biologically inspired real-time information processing on tactile sensor arrays, wave computing, CNN-UM, autonomous robots, integrated tactile and vision systems and smart sensors.