Micro- and nanoforce sensors

PhD thesis booklet

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I. Background

I have done my research at the Centre for Energy Research Institute of Technical Physics and Material Science MEMS Laboratory. 1µm resolution 4 inches technology-equipped clean room is being operated in the Laboratory for developing MEMS (micro-electro mechanical system) devices. Sensors under investigation include pressure sensors, gas sensors, energy harvesters, brain electrodes and 3D force sensors. 3D force sensors had already been studied for several years when I joined in the work in 2013 [1]–[3]. At that time the very first SOI (silicon-on-insulator) based force sensors were designed. SOI wafers ensured homogeneity within the wafer and the tuneable sensitivity through the membrane thickness. Additionally, also at that time the alkaline wet etching process was replaced with deep reactive ion etching (DRIE) method. DRIE allowed us to design vertical sidewalls for the joystick and the hollow around the joystick.

II. Goals

Among my first tasks were to take part in the fabrication process of the 3D force sensors as well as to design and assemble a purpose-built test station for the characterization of the accomplished sensors. My main goal was to demonstrate the 3D functionality of the force sensors by means of the achieved 3D measurement system. Besides, I also examined the effect of the elastic polymer coating.

As a participant of ENIAC INCITE international project, my next task was to miniaturize the silicon sensors. The project focused on a smart laparoscope for measuring the gripping force and the flexibility of the touched tissue using our force sensors. My work aimed the realisation of the tiniest silicon based MEMS force sensor for integrating into the surgical gripper. Moving further with downscaling my interest turned towards submicron-size piezoelectric nanorods. With that work I joined another international project (PiezoMat) as well.

After the design, fabrication as well as characterization of the miniaturized force sensor I also took part in the integration process into the tweezers. I played a large part in the design of the gripper which was critical for the force measurement.

Another topic of my PhD work was to integrate the accomplished force sensor into the inner sidewall of a vehicle tyre for the real-time monitoring the acting forces between the road surface and the tyre-tread. I developed the patent protected sensor in the frame of the national program, KOFAH.

III. Experimental methods

a) The characterization of the MEMS force sensors was firstly carried out with a goniometer based manual test station. After that I designed and built a fully-automated apparatus from Thorlabs linear and rotation motors. National Instruments data acquisition cards were used for driving and reading out the sensors. For the communication between the cards and computer I wrote a software in LabView environment. Andilog Centor Easy calibrated force sensor was used for measuring the load force.

b) Weiss WKL60 climate chamber was applied for temperature and humidity tests.

c) Characterization of nanorods was accomplished with an AIST NT, Smart SPM 1010 atomic force microscope.

d) The properties of nanorods were examined with a LEO GEMINI scanning electron microscope. When it was needed the cross-sections of nanorods were formed with focused ion beam.

e) The biomechanical tests of surgical grippers were carried out with Robin Heart surgical robotic system developed by the Polish FRK (Foundation for Cardiology Development).

f) The tyre sensor tests were realized with an automotive electric Nissan Leaf operated by SZTAKI (Institute for Computer Science and Control).

IV. Theses

1, I firstly examined the direction dependence of piezoresistive force sensors and experimentally verified on tool of different geometry size, with special emphasis on miniaturization. The measured sensitivity were 8.3 mV/N/V for 940 µm diameter non-perforated membrane with 50 µm thickness; 57.5 mV/N/V for perforated membrane with the same sizes; 16.0 mV/N/V for 500 µm diameter non-perforated membrane with 50 µm thickness 75.7 mV/N/V for the same diameter non-perforated membrane with 20 µm thickness. They fitted well with the results of the Comsol Multiphysics simulations [S1], [S2], [S3] *(Section 5.-6.)*.

2, I determined experimentally the effect of elastic coating on the sensitivity of the force sensor. I found that a 1 mm thick PDMS coating on a 500 µm diameter membrane with 50 µm thickness decreases the sensitivity till 0.84 mV/N/V, i.e. to 1/20, and increases the response time from 36 µs to 60 µs [S1], [S3] *(Section 5.-6.)*.

3, I have worked out a measurement procedure for studying lateral load of piezoelectric nanorod based force sensor using scanning probe microscope. The sensitivity of submicron piezoelectric semiconductor ZnO nanorod was between 2-15 mA/N. [S4] *(Section 7.).*

4, I firstly applied semiconductor based piezoresistive MEMS force sensor, integrated into a surgical gripper as tactile sensor, to distinguish different organs. With a smooth movement after touching the tissue 200 mN/mm and 125 mN/mm average elasticity parameters were measured for bone tissue and soft tissue (skin and muscle), respectively [S1], [S2], [S5], [S6], [S7] *(Section 8.).*

5, I have worked out a procedure for embedding a force sensor into a surgical gripper so that the sensor sinks underneath the grasp plane of the gripper while the polymer coating protrudes 200 µm from the plane. In that way the gripper fits to the requirements of the robot-developer that is the measure range of the sensor is 20 N at the most and damage threshold is over 100 N [S1], [S2], [S5], [S6], [S7] *(Section 8.)*

6, I have worked out a patent-protected procedure for embedding 3D force sensor into inner sidewall of a vehicle enabling the in-situ monitoring of driving dynamics of a vehicle [S8] *(Section 9.)*

V. Exploitation

The results of theses 1 and 2 are essential for getting know the pros and cons of silicon based force sensors and in view of this knowledge new applications may be available. The results of thesis 3 were partly used in accomplishing of a high resolution finger print sensor in the frame of PiezoMat project. The results can be also useful for investigating of other nanorods based sensors such as artificial skin.

The successful demonstration of laparoscope was based in part on the results of theses 4 and 5 which contributed to participate in the Position-II project as a follow-up of Eniac Incite. Additionally, further developing of the surgical gripper can help the success of the robot assisted interventions.

Finally, the results of thesis 6 can improve the efficiency of driving dynamics monitoring systems of a vehicle and can contribute to development of the automotive vehicles.

VI. References

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VII. Publications related to theses

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[S2] Radó, Janos, Csaba Dücsö, Péter Földesy, Gábor Szébenyi, Hunor Sántha, Kamil Rohr, Lukasz Mucha, Krzysztof Lis, Wojciech Sadowski, Dariusz Krawczyk, Piotr Kroczek, Zbigniew Małota, Zbigniew Nawrat and Péter Füijes, “Force sensitive smart laparoscope of ROBIN HEART surgical robot,” in *Symposium on Design, Test, Integration and Packaging of MEMS/MOEMS*, DTIP 2018, 2018, pp. 1–4., number of citations: 1

[S3] Radó, J., C. Dücső, G. Battistig, G. Szebényi, G. Szebényi, P. Fürjes, Z. Nawrat and K. Rohr., “3D force sensors for laparoscopic surgery tool,” in 2016 *Symposium on Design, Test, Integration and*

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[S8] J. Radó, A. Nagy, and J. Volk, "Jármű gumiabroncs menetdinamikai állapotát mérő eszköz," U 19 00189, 2019.

Further publications not closely related to the subject of this work:

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VIII. Further publications

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[2] János Radó et al, „Mechanical Energy Harvester Assisted Wireless Sensors”, WMRIF, Budapest 2019

[3] János Radó et al, „Biomechanical tissue characterisation by force sensitive smart laparoscope of Robin Heart Surgical Robot”, Eurosensors, Graz, 2018

[4] János Radó et al, „Low-frequency piezoelectric accelerometer array for fully implantable cochlear implants”, Eurosensors, Graz, 2018

[5] János Radó et al, „Force sensitive smart laparoscope of Robin Heart Surgical Robot”, DTIP, Rome, 2018

[6] Radó János, „Tapintásérzékelés az orvosi robotikában”, MTA előadás, Budapest, 2017

[7] János Radó et al, „Thermal noise limited, scalable multi-piezoresistor readout architecture”, Eurosensors, Paris, 2017

[8] Radó János, „MEMS technológiával előállított 3D erőmérő szenzorok”, Kandó Konferencia, Budapest, 2017

[9] János Radó et al, „3D force sensors for laparoscopic surgery tool”, DTIP, Budapest, 2016

[10] János Radó et al, „Monitoring the tyre deformation on a vehicle on the run”, Eurosensors, Budapest, 2016

[11] János Radó et al, „3D force sensors for laparoscopic surgery tool/for surgery robotics”, Roboty Medyczne, Zabrze, 2016

[12] Radó János et al, „3D mikro-erőmérő sebészrobot alkalmazáshoz”, OATK, Balatonalmádi, 2015

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[13] Miklós Szappanos et al, „Energy Harvesting Powered Wireless Vibration Analyser”, Eurosensors, Graz, 2018