České vysoké učení technické v Praze, Fakulta elektrotechnická

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Taktilní senzory a jejich využití v robotice a biomechanice

Tactile sensors and their Using in Robotics and Biomechanics

SUMMARY

The thesis deals with a construction of tactile sensors and their usage in robotics and biomechanics.

The first part deals with the terminology used in the science of tactile sensors, transducers and the usage of tactile information.

The following part of the thesis describes the most common principles and constructions of tactile sensors and transducers. The prime focus is on sensors based on conductive elastomer FSR and DLR sensors. Also the strain gages sensors, piezoelectric sensors, optical fibre sensors and transducers are described.

The third part of the lecture deals with the usage of the tactile sensors and transducers in robotics and biomechanics.

Firstly usage in robotics is depicted. Various robot's gripping hand with tactile sensors for gripping force control.

Finally usage in biomechanics is depicted. A measure system Plantograph which is used for measurement of pressure distribution on soles is described. Plantograph measure system was awarded in 1998 by 1st price of Innovation in the Czech Republic and in 2005 by Certificate of Meritn (2nd place in Price of Innovation in CR). Then the thesis deals with sensor for stress field in bone, transducer of pressure distribution in knee joint replacement and transducer for occlusion measurement. Lastly the human hand replacement and non traditional usage of tactile information is described.

Most sensors described in this thesis has been developed by the author and his research team, some of them are protected by patents.

SOUHRN

Teze jsou věnovány konstrukci taktilních čidel a jejich využití v robotice a biomechanice.

První část se zabývá použitou terminologií v oboru taktilních senzorů, snímačů a užití taktilní informace.

Další část tezí popisuje nejčastěji používané principy a konstrukce taktilních senzorů a snímačů. Hlavní pozornost je věnována senzorům na bázi vodivého elastomeru, FSR a DLR senzorům. Své místo zde našly i tenzometrické senzory a piezoelektrické senzory a optovláknové senzory a snímače.

Třetí část tezí se věnuje užití taktilních senzorů a snímačů.

V ní je nejdříve pozornost upřena na jejich použití v robotice. Jsou zde uvedeny různé úchopné hlavice robotu, osazené taktilními senzory pro kontrolu úchopné síly.

Závěrem je zaměřena na užití taktilních senzorů a snímačů v biomechanice. Je zde popsán měřicí systém Plantograf, určený k měření rozložení tlaků na ploskách chodidel. Tento Plantograf byl v r. 1998 oceněn Cenou Inovace roku 1998 (1. místo), udělenou Asociací inovačního podnikání ČR a v r. 2005 Čestným uznáním Ceny Inovace roku 2005 (2. místo). Dále se zabývá snímačem pro snímání napětí v kostech, snímačem rozložení tlaku v náhradě kolenního kloubu a snímačem měření skusu. Dále je pozornost věnována náhradě lidské ruky a netradičnímu užití taktilní informace.

Většina těchto taktilních senzorů a snímačů byla vyvinuta na pracovišti autora pod jeho vedením, řada z nich je kryta patenty.

Klíčová slova

taktilní senzory, taktilní snímače, vodivý elastomer, piezoelektrické senzory, optovláknové senzory, FSR, DLR, tenzometry, měření síly, měření rozložení tlaku, Plantograf, protéza, taktilní informace, robotika, biomechanika

Key Words

tactile sensors, tactile transducers, conductive elastomer, piezoelectric sensors, FSR, DLR, strain gages, force measurement, pressure distribution measurement, Plantograph, replacement, tactile information, robotics, biomechanics

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OBSAH

1 INTRODUCTION

Let us start by a question: Why to use tactile information? Nature gives us the answer: The sense of touch is one from five of human senses. Somebody can complain that humans get most information by sight. Yes, it is a fact, but what a blind person can do? And we are near of a crux. Touch is one of the most important and irreparable senses. Somebody could complain again, that majority of people can still see. Yes, but at the time when we switch off, what do we do in full darkness? How would we orientate? – by using touch again. I believe that each of us has dealed with such a situation. Consider a robot capable of gripping objects of different mass and solidity that even can glide. Here the tactile information is irreparable again. What about the people who lost the hand for any reason? Artificial touch (and tactile information again) can markedly improve their life. These are just examples. More reasons for using tactile information and tactile sensors may exist.

2 SHORT HISTORY

The group of Japanese scientists by heading of prof. Kinoshita [26], [27] created tactile transducer with 22 on-off switches, which were suitably placed on an artificial five fingers hand surface, see Fig.1.

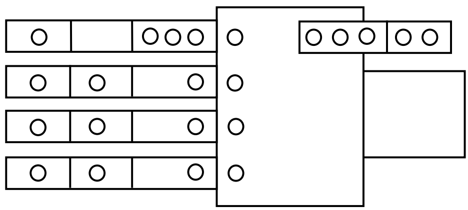


Fig. 1 Placing of switches on hand surface

Data from micro-switches were processed by an adaptive classifier. A subject must be gripped by 6 specified ways in order to achieve 50% of right classification of cylinders and prisms dimensions. The information character is stochastic in this case.

At the Department of Control Engineering (in this time Department of Cybernetics) of Faculty of Electrical Eng. of CTU in Prague transducer was designed and realized. This transducer is created by potentiometer in fingers joints [28]. This hand is an analogy of a human hand. Potentiometer’s data were processed by a net of an adaptive threshold element with automatic structure selecting. A right pattern recognition from 86 to 100 % was reached for large dimension of cylinders, n-sides prisms, cones, pyramids and balls only by one single grip. The palm was finalized by adding a tactile transducer with 659 sensors and and by using of linguistic system (described in the reference [29]). By that right pattern recognition was increased to 96 %. Fig. 2 shows a photography of this hand.

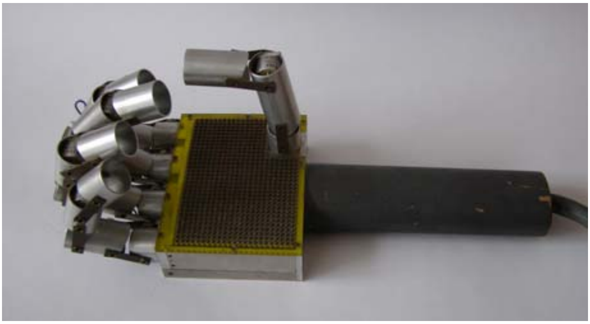


Fig. 2 Anthropomorphic gripping hand

Next method that was used for tactile pattern recognition was active sensing. Prof Aida [26] used one finger with four on-off switches, which were able to sense the object surface. Other system SATR [30], [27] employed information theory [30]. This system determined local object design in touch point. Right pattern recognition reached 90-100 %.

3 GENERAL NOTIONS

Tactile sensors and transducers enable to obtain specific information, which is not possible to obtain by other way and it is necessary for interaction among different objects and subjects. They enable robots protection, subject soft gripping, moving by kinematics limiting, action by force or torque in a given direction, accuracy space coordinates measurement etc.

For better orientation within this subject we describe selection and specification of tactile sensors. Let's start by defining a tactile sensor.

Tactile sensor is an element, which is able to scan information in regard to touch with outside area element and to convert it into an electrical signal.

Tactile transducer is usually a matrix or different geometrical tactile sensor organization.

According to the process of collecting tactile information, the tactile sensors can be divided into:

1. **primary** – tactile sensor, which goes to direct contact to gripped subject; here is inserted more of tactile sensors,
2. **secondary** – tactile sensor, which captures tactile information vicariously; proximity sensors are sometimes included.

By output signal sensors can be divided into 2 groups:

1. **proportional** – tactile sensor that output electrical signal has continuous character,
2. **discrete** – tactile sensor that output electrical signal is logical.

Tactile sensors are placed on a very exposed area. Besides the evident exigencies for accuracy and reliability, other relatively strict requirements are put on tactile sensors.
They are:

1. **small size** - the sensors are placed on the surface of the active gripping head and must not interfere with its function,
2. **little mass** - affects the dynamic responses of the servo system manipulating of the robot,
3. **great mechanical robustness** - the sensors must not be damaged during the activity of the robot,
4. **transmission linearity** - in a certain range of the pressure affecting the proportional sensor (there must exist a simple possibility of adjusting the switching threshold of discrete tactile sensors),
5. **on - line connection** - of the sensor with the device achieving the further processing of the gained information.

The tactile arrangements have a lot of advantageous qualities, which lead to their application in the sensing system of the robot. The tactile transducers and sensors are small and light devices, which can be integrated in the gripping head. This quality results in possibility of changing the working space. They are also feasible to record parallel of the operating data in real time. The exigencies for the computing techniques are small. In comparison with the visual systems, where the falling shadows may cause errors, the tactile transducers are to a certain extend independent on the surrounding influences. The relatively simple possibility of obtaining the output signal in a digital form is also another advantage of the tactile transducers.

The robustness of tactile transducers is limited in comparison to the visual systems, which is caused by the influences of the mechanical design. The disadvantages of the tactile transducers are the minimum necessary gripping force and an increased wear probability.

4 CONSTRUCTION OF TACTILE SENSORS

4.1 Tactile sensors based on conductive elastomer

There is an electrical conductive elastomer used as force – electrical signal converter. This elastomer changes its resistance by acting force. In principle this elastomer is made of silicon rubber saturated by graphite or iron powder. By processing of resistance variation we get information about the gripped object. Such transducers exist in many variants. For instance, an area transducer designed with solid plate of conductive elastomer or as a multiplicity of simple small sensors. At the author's workplace were designed many sensors and transducer, based on this elastomer. These transducers were meant for using in robotics cf. [1], [3], [4] or for using in biomechanics, see [6], [9], [14], [15].

Measuring devices using conductive elastomer exhibit good quality. They indicate not only simple contact but also can give quantitative information, as they can be arranged in a matrix of elementary sensors. These elements made of conductive elastomer [2] in a matrix can measure the pressure affecting each element in several quantisation levels. Fig. 3 shows the primary construction.

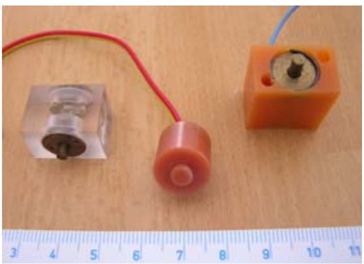


Fig. 3 Primary construction of tactile sensors

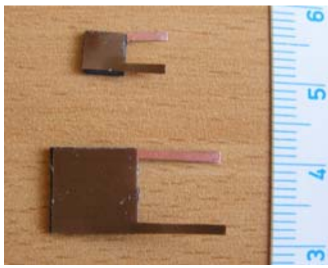


Fig. 4 The construction of PMT 1.4

The transducer PMT1.4 was tested for robotics and biomechanics. Design of the transducer PMT1.4 is shown in Fig. 5, real design in Fig. 4.

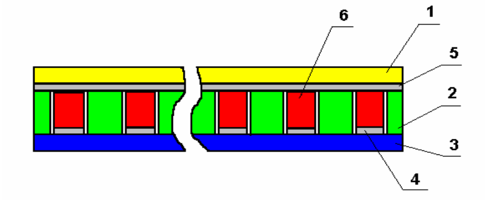


Fig. 5 The construction of PMT 1.4

The conductive elastomer 6 is located between a pair of the electrodes 4 and 5. One of these electrodes 4 is placed on the basic plate 3 and the second one 5 on the elastic covering foil 1. This foil transfers axial pressure force onto the conductive material 6. The distance insert 2 serves for an adjustable working range of the sensor and for the mechanical protection of the conductive material against overloading. The transducer has no moving mechanical elements.

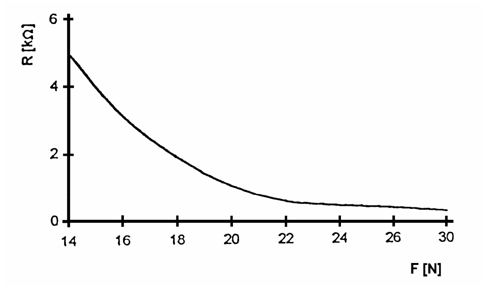


Fig. 6 The dependence R = f(F)

Fig. 6 presents the dependence of the resistance R on the axial pressure force F. The relation between the load on the transducer and the deformation of sensing elements is not linear in the whole range. The sensor output voltage is a non-linear function of the affecting force but can be easily linearized electronically.

Another construction of the transducer PMT 1.3 is described by Fig. 7 and real design for one sensor by Fig. 8. Both electrodes 4 are placed on basic plate 3 there. They have a specially designed shape. The conductive elastomer 5 lies in this case on electrodes 4. The other layers are identical as in transducer PMT 1.4.

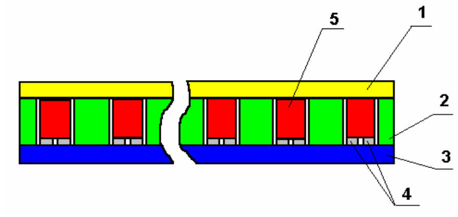


Fig. 7 The construction of PMT 1.3

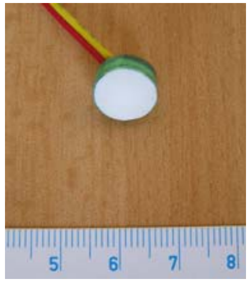


Fig. 8 Design of PMT 1.3

Fig. 9 shows construction of the transducer with matrix sensor selection and area conductive elastomer 3. Electrodes 4 and 5 are as strip created. Other layers are identical as in transducer PMT 1.4, only they have other number. More information can be fond in [3], [5], [6], [9], [11].

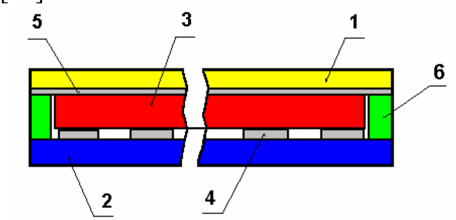


Fig. 9 The construction of transducer with area elastomer

The foil of conductive elastomer is the main part of the transducers. The foil is 0,5 mm thick material CS 57-7 RSC Yokohama Rubber Co. [2]. Using this material, we received not only mechanical durability, but some other advantages, too. (i.e. almost stable state of some electrical and mechanical properties).

Tab. 1 describes properties of conductive elastomer type: CS 57-7 RSC (Yokohama Rubber Co. Ltd., Japan).

Tab. 1 Properties of conductive material

Colour	black	
Thickness	0,5	mm
Tensile strength	1,9	N/mm^2
Elongation at break	220	%
Temperature range -	40 to 100°C	
Tear resistance	7	N/mm
Maximal load	1,4	MPa

No important changes in the elastomer properties after 1 million loading cycles have been observed. The temperature vs. force dependence is quite acceptable for us as well, because the transducer will be used in heated medical spaces (e.g. in surgery rooms - assumed temperature: 20-30°C; for the accession to the transducer - local maximum 35°C is considered).

4.2 FSR tactile sensors

These sensors are resistive sensor based on resistance change of polymer layer (Resistive Film or FSR Polymer Ink).

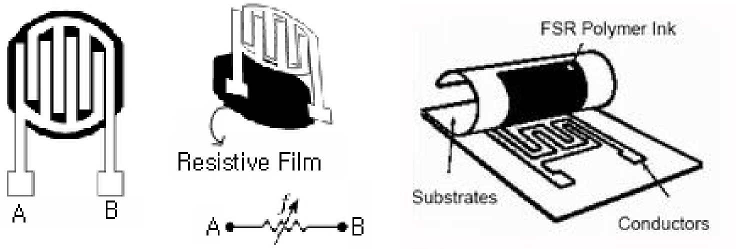


Fig. 10 Design of sensors

The resistive element is made by the technology of conductive thick polymer layers (PTF). The layer is created from electrical conductive and nonconductive elements. By loading of the sensor, these elements get in contact and the resistance of layers decreases. The main advantage is the possibility to create the sensor in different shape (e.g. long strip) or a large transducer area. Typical loading is to 10 N, possible is to 100 N, and typical resistance range is form 2 MΩ to 2 kΩ. Fig. 10 shows design of these sensors and Fig. 11 loading response.

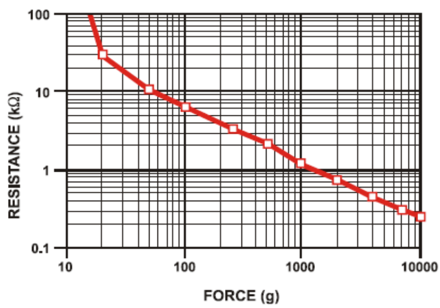
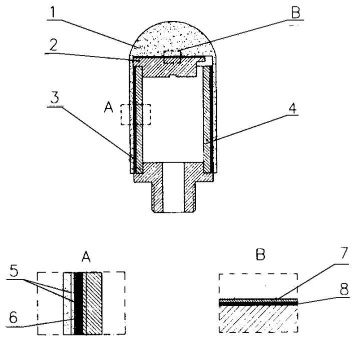


Fig. 11 Loading response

The DLR sensor [16], [17], based on FSR, is showed on Fig. 12. Tactile strain gage sensors and transducers



1. rubber cover
2. tip sensor supporter
3. joint connector
4. supporting core
5. flexible circuit
6. FSR material
7. flexible circuit
8. FSR material

Fig. 12 DLR sensor construction

4.3 Tactile strain gage sensors and transducers

These sensors measure deformations generated by acting force on robots elements, e.g. on grab. As the converter between force and electrical signal strain gages are used.

Currently, semi-conductive strain gages are most often used. These strain gages are from 50 to 100 times more sensitive and they have miniature dimensions. They are more sensitive to temperature, too. By next formula we can compute resistivity of glued strain gage [55]:

$$R_{\varepsilon,t} = R_{0,25}(1 + a(t-25) + b(t-25)^2) + \\ + R_{0,25}[1 + C_1(\varepsilon + (\alpha_{mat} + \alpha_{Si})(t-25)) + \\ + C_2(\varepsilon + (\alpha_{mat} + \alpha_{Si})(t-25))^2]$$

where

$R_{0,25}$ of non-glued strain gage by 25°C (Ω)
$R_{\varepsilon,25}$ resistivity of deformed strain gage by stationary temperature 25°C (Ω)
C_1 linear coefficient of deformation equation
C_2 quadrate coefficient of deformation equation

a,b	temperature coefficients of non-glued strain gage resistivity
ε	relative strain (m/m)
t	temperature (°C)
α_{mat}	coefficient of material thermal expansibility, where strain gage is glued
α_{Si}	coefficient of silicon thermal expansibility – 2,8 10^{-6} (1/°C)

At author's work place was developed special transducer for measurement for measurement of stress field in bone [36] and [37]. For this transducer, the company VTS Zlín developed special semiconductive strain gage that is 2 mm in length and the terminal wires are on one side.

4.4 Tactile piezoelectric sensors

These sensors are elementary. Originally crystal was used, now other materials with similar properties: piezoelectric ceramics, polyvinylidenfluorid (PVF_2) etc. Small dimensions are an advantage of these sensors. Their big inside resistance is a disadvantage, so that input resistance of processing circles about 10^{12} Ω must be used. Another disadvantage is that the charge amplifier must be used for measurement of static force. The piezoelectric resonator is the main element of this tactile sensor type. The properties of the sensor are given with piezoelectric and elastic coefficients and modules, and on geometrical dimension of the cut. The parameters are influenced the most of all by the way of placement of the piezoelectric resonator in the tactile sensor.

At the author's work place new sensors was developed that enabling measure static force without charge amplifier [4],[20], [21].

In [20] and [21] are described two constructions of sensor that are shown on Fig. 13 and Fig. 14. Both constructions used the elastic joint 6. This construction respects big problem with elastic placing and fixing of piezoelectric element 5. The piezoelectric elements have dimension 2x2x1 mm. On Fig. 13 is piezoceramic element exposed propeller shaft between both electrodes, on Fig. 14 ceramic

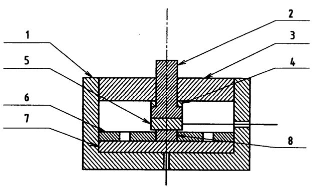


Fig. 13 Design of PZTC-1

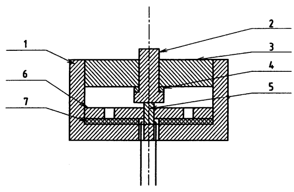


Fig. 14 Design of PZTC-3

element has terminals soldered.

Loading response for ceramics PZK 850 is showed on Fig. 15 and Fig. 16.

Fig. 15 shows dependence oscillator output voltage on sensor loading PZTC-1. Output response isn't linear, which is evocated by ranch 0 – 5 N. Next response is linear. The dependence equation is $y = -0{,}0141x^2 - 1{,}6956x + 562{,}28$ by correlation R = 0,996. The sensor has average sensitivity C = - 2,09 mVN^{-1}. The used loading range is 0 – 50 N. We assume that the available loading can be bigger, but the loading equipment could not provide any additional load.

Fig. 16 shows dependence of output voltage on loading by sensor PZTC-3. This response is linear and described by equation
$y = -0{,}676x + 707{,}95$ by correlation R = 0,9383. The unambiguously measurement range is here 0 – 50 N. by sensitivity C = -0,82 mVN^{-1}. High range was limited by possibilities of loading equipment again.

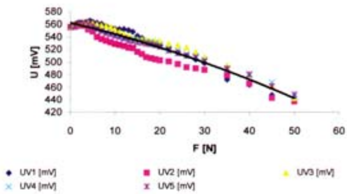


Fig. 15 Loading response of PZTC-1

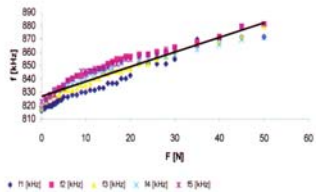


Fig. 16 Loading response of PZTC-3

Used piezoelectric material PZK 850 has followed basic parameters:

density	$7{,}6.10^3$ kgm^{-3}
relat. permittivity	1750
Curie's temp.	360 °C
piezoel. coefficients:	
d_{31}	-180.10^{-12} mV^{-1}
d_{33}	380.10^{-12} mV^{-1}
factor of quality	80
speed of lengthwise wave diffusion	2 833 ms^{-1}
dimension:	
thickness	1 mm
latitude	2 mm
lengths	2 mm

For used material PZK 850 we can compute basic parameters of sensor.

Speed of lengthwise wave diffusion:

$$c = \sqrt{\frac{1}{\rho\, s_{11}}} = \sqrt{\frac{1}{7{,}6\,.\,10^{3}\ .16{,}4\,.\,10^{-12}}} = 2832{,}51 \qquad \mathrm{ms^{-1}}$$

Now we calculated resonance frequencies, which corresponded with geometrical resonator dimensions.

Resonance frequency of thickness vibration:

$$f_r^{\,t} = \frac{c}{2a} = \frac{2832{,}51}{2\,.\,1\,.\,10^{-3}} = 1\,416{,}255\,.10^{3} \qquad \mathrm{Hz}$$

Resonance frequency of latitude vibration:

$$f_r^{\,b} = \frac{c}{2b} = \frac{2832{,}51}{2\,.\,2\,.\,10^{-3}} = 708{,}128\,.10^{3} \qquad \mathrm{Hz}$$

Resonance frequency of lengthwise vibration:

$$f_r^{\,l} = \frac{c}{2l} = \frac{2832{,}51}{2\,.\,2\,.\,10^{-3}} = 708{,}128\,.10^{3} \qquad \mathrm{Hz}$$

4.5 Optical tactile sensors and transducers

Optical fibre sensor is based on deformation of an optical fibre caused by acting outside force. The fibre deformation affects the modulation of the signal carried by the fibre. It is possible to influence phase, amplitude, polarization or the spectral function of signal transmitted through the fibre optic link. The optical sensor must be fed by some light power (laser, laser diode) and the output detector analyses the intensity of the changes. The advantage of the optical fibre sensors is the immediate continuity and its supplies. Sensor can work as a passive element without influencing the quality of input signal. Optical fibre sensors are insensitive to outside electromagnetic areas, enable to transmit information among objects with different electrical potentials and they can transmit information in high frequency an on a long distance.

Fig. 17 represents the micro bending sensor. Change of transmitted power is the principle of this sensor. This change is invoked by bending the fibre, which contribute to increase of the optical losses. This transducer poses high requirements on the quality of the detector.

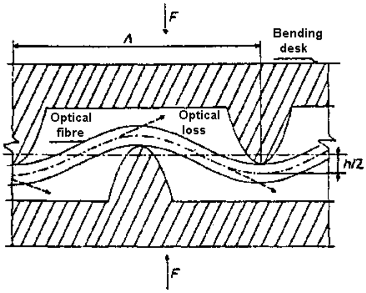


Fig. 17 Micro bending sensor

The matrix transducer based on micro bending sensors is shown in Fig. 18. The disadvantage of this transducer is the big number of feeding and receiving elements.

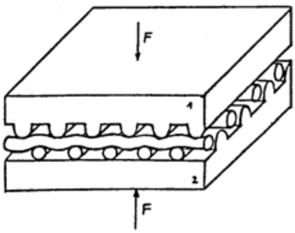


Fig. 18 Matrix transducer

The condition of total reflection disturbance is used by these sensors. For total reflection it obtains:

$$\Theta_c \geq \arcsin \frac{n_2}{n_1}$$

where

θ_c	incidence angle
n_1	kernel refraction index
n_2	cover refraction index

A critical radius of curvature, when losses strongly rise, we can calculate by form:

$$R_k = \frac{3n_1^2\lambda}{4\pi(n_1^2 - n_2^2)^{\frac{3}{2}}}$$

where

n_1 kernel refraction index
n_2 cover refraction index
λ wave length

The critical micro bending Λ_c (see Fig. 17) we can calculate by next form:

$$\Lambda_c \frac{\sqrt{2\pi a n_0}}{NA}$$

where

a kernel radius
n_o refraction index in kernel centre
NA numeric aperture NA = sin Φ_{1c}
Φ_{1c} max. angle to kernel centre line that total reflection exists between kernel and cover

Fig. 19 presents a sensor as an optically coupled element. Two fibres are in contact and are ground together. By suitable design of parameters (length of the connected fibres area / and the angle α), it is possible to reach transmission of a part of the power to the second

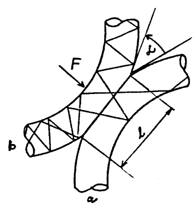


Fig. 19 Optical coupled element

fibre by exciting first fibre.

Fig. 20 shows a tactile sensor in which the transparent material elasticity is used. It is possible to use the known losses dependence to design optical sensor based on connection of optical fibres couple.

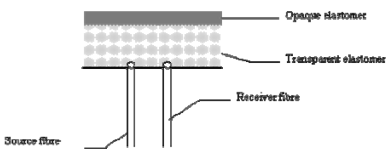


Fig. 20 Optical sensor with transparent material

5 USING OF TACTILE SENSORS AND TRANSDUCERS

5.1 Using of tactile sensors and transducers in robotics

Robotics presents the oldest and the most frequent usage of tactile information in the industry. At the beginning tactile transducers were used only for subject gripping indication in robotic gripped hand, then for gripping control, slip measurement or accuracy subject positioning.

Expressive expansion of service robots is expected in situations, where they can provide support to people in different areas, e.g. in dangerous territories (chemical, radioactive areas or otherwise life dangerous), in critical and differently wrecking situations, further more by taking care of patients and handicapped persons, by rehabilitation, eventually as a home helper. Robots must be equipped enough with an intelligent control system that could enable them to move in a human natural environment. That requires an universal anthropomorphic gripping hand. These hands can have three to five fingers and supplied by different sensors type.

Three fingers hand for industrial usage is shown in Fig. 21 and is described in [16] - [18]. This hand is supplied by the sensors DLR type. Another three fingers hand is described in ref. [45], see Fig. 22. All hands are equipped by intelligent control gripping feedback.

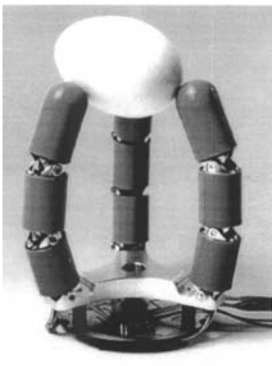


Fig. 21 Three fingers hand with DLR sensors

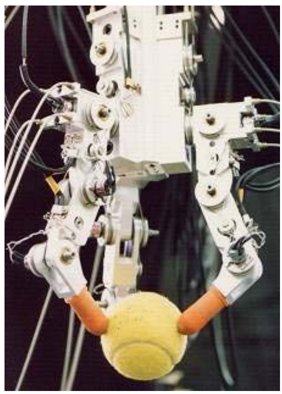


Fig. 22 Three fingers hand

In [47] is described four fingers hand that was developed in German centrum for aviation and astronautics. The last phalanges are supplied by sensor DLR and every joint by torque sensor, see Fig. 23. To the hand are integrated drive units, power and communication electronics. By this way a hand flexibility and operability in unknown surroundings are enabled. This hand is able to hand out a coffee or tee cup as well catching a warped ball.

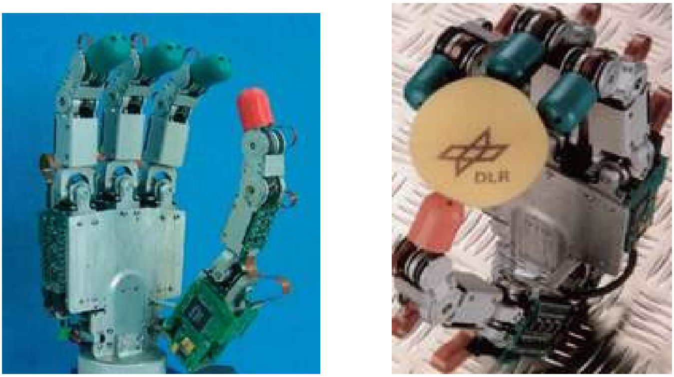


Fig. 23 Anthropomorphic four fingers hand with DLR sensors

Another four fingers anthropomorphic hand shows Fig. 24. This hand was developed on Tokyo University and is supplied by two layers sensor for gripping force and slip measurement.

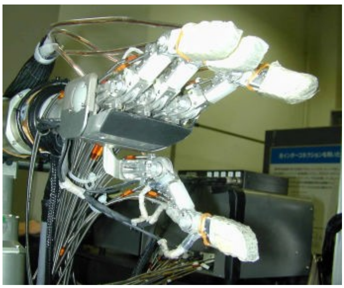


Fig. 24 Anthropomorphic four fingers hand

The soft interactive human robot RI-MAN presents top of the artificial intelligence usage. This robot was developed in RIKEN, Bio-Mimetic Control Research Centrum in Japan [51]. The robot has ability to assist in human care and in social tasks. The RI-MAN can be a partner robot. General look on the robots shows Fig. 25. Fig. 26 sows the RI-MAN with patient in fold. The robot communicates by human voice, it is scanning the surroundings by using two cameras, it is able to orient itself in this scene in the real time, reacts on commands, which meanings it receives and analyzes. By these commands it controls its activity. This robot has an olfaction, hearing and tactile sensors for bio-feedback, see Fig. 27. The RI-MAN is determined to work in hospitals, social arrangement, by manipulations with patients, their nursing and servicing.

Fig. 25 Robot RI-MAN

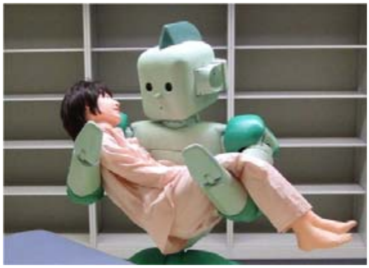


Fig. 26 Robot RI-MAN with patient

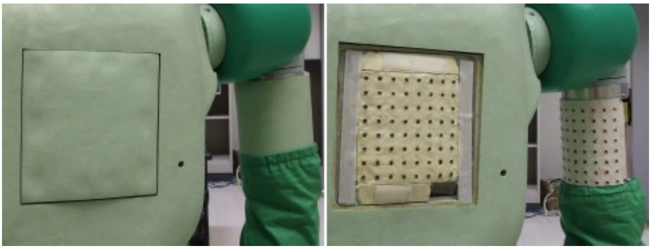


Fig. 27 Tactile sensors of RI-MAN

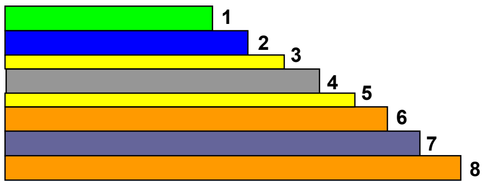
5.2 Using tactile sensors and transducers in biomechanics

5.2.1 Plantograph

The flexible pressure area transducer has been developed mainly for medicine purposes, to design the sitting profiles for paraplegics; and to realize the preventative feed-back element of the pathological press-through places generation on the human body („bedsores“).. Having mentioned properties, this measuring system can be used in some other branches.

Mentioned transducer was developed on author’s workstation of Faculty of Mechanical Eng. of CTU in Prague [6] – [10], [22] and [23] with cooperation with Faculty of Electrical Engineering CTU in Prague, Faculty of Physical Education and Sport Charles University and Rehabilitation Clinic of CU Hospital in Vinohrady in Prague.

The core of the construction of the transducer (see Fig. 28) is created by conductive elastomer which is situated between two area electrodes. The polyamide substrate guarantees enough flexibility of the upper electrode. For the better chemical stability and for the guaranteed conductivity, the surface of Cu-electrodes is gilded. To get enough the mechanical transducer's independence, the electrodes outputs with the sufficient length are divided into the sessions. Thickness of upper electrode is only 0,05 mm. The upper electrode has 75 column-belts; and the lower electrode has 100 row-belts. Having perpendicular electrodes arrangement, we receive 7500 sensing elements in the cross-section points. This construction is protected by patent and utility design [32] and [33].



1 - cover layer	5 - down electrode CUFLEX
2 - slip layer	6 - antistatic layer
3 - top electrode CUFLEX	7 - dural plate
4 - conductive elastic material CS 57-7 RSC	8 - antistatic layer

Fig. 28 Transducer arrangement

Technical parameters are showed in Tab. 2.

Tab. 2 Technical parameters

Patient Mass	to 120 kg
Rated Pressure Range	5 - 80 kPa
Permissible Overload	1.4 MPa
Transducer Activated Area	400 x 300 mm
Transducer Dimensions	750 x 650 mm
Sensing Elements Number	7500 pcs
Dimension of Sensor	2x2 mm
Resolution	4 mm
Transducer Supply Voltages	+ 5V; + 12 V
Transducer Analogue Output	to 1V
Digital Output	256 levels (8 bits)
Number of Snaps	60 snaps/200ms
Snap Frequency	300 Hz
Sampling Frequency	2.5 MHz

In order to achieve full utilization of the A/D converter, the sensitivity can be altered. The transducer has been realized with the grid-resolution 4 mm. The sensitivity can be further adapted, either by using the various cover layers, or electronically.

The transducer can work in two modes:

Continual Visualization - displays the actual pressure distribution on the transducer in real time. The speed acquisition data is up to 50 snaps/second depending on the computer processor speed. This mode is mainly used, either for the parameters setting (to be immediately checked) to the later precise measurement; or for the single–shot snaps acquisition. Then, these can be stored.

Accuracy Measurement - no display of the data measured. The data are recorded on the internal hard disk (HDD) – for the later PC-transfer. The speed is up to 300 snaps/second. The disk capacity is free (e.g. common IDE ATA HDD). The several records can be stored on the disk at once, for the later one–snap PC data logging.

Full system is showed on Fig.29. Fig 30 then one of output presented images in 2D or 3D projection.

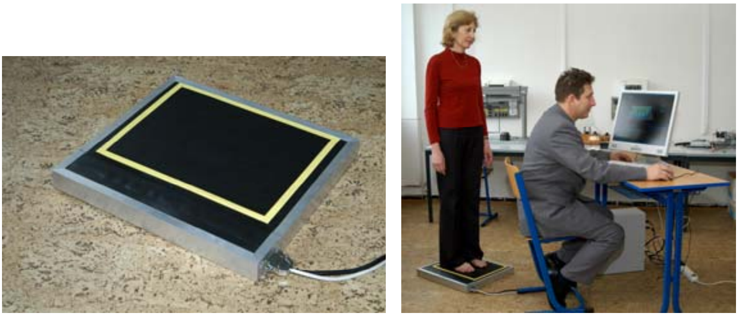
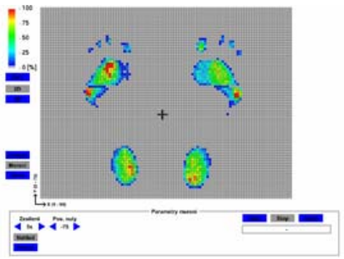


Fig. 29 Plantograph measure system

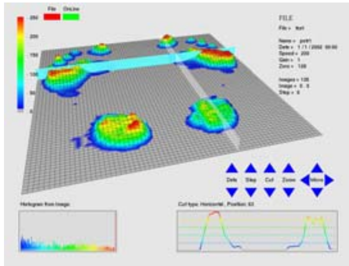
On Fig. 30 a) and b) healthy soles in 2D and 3d projection, c) and d) are flatfoots, on e) ballet girl stand and on f) sitting on car seat in ŠKODA car.

SW enables not only visualization and data logging, but also the fundamental processing. Vision tools enable:

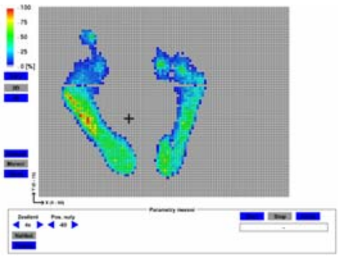
- To display any snap-shot from the recorded waveform. The demanded snap can be extracted, either in accordance with its snap-time, or in accordance with the waveform snap – number.
- X- and Y axis snaps rotation; zooming.
- In both directions, the motion control is running in recorded time.



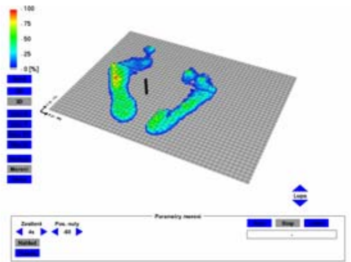
a)



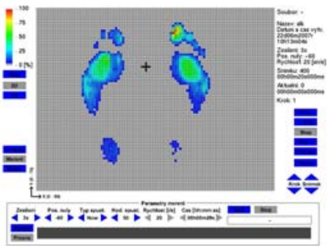
b)



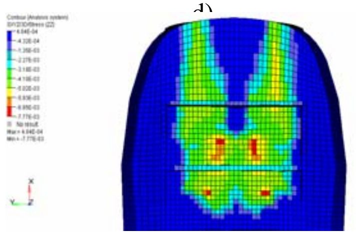
c)



d)



e)



f)

Fig. 30 Shows of measured data

- For snap, to display the main pressure centre (the balancing point – COP).
- In snap, it is possible to create the local/separate regions with the own local pressure centers.
- Creating of the own horizontal and vertical cuts. Each one can have its own interactive motion profile – to be seen in the waveforms in the extracted cuts.
- The customized creating of the color scale/palette (pressure/color). Being used e.g. for capturing any interesting pressure levels - by means of any special color.

- To create video recording from stored data (possible to play on any PC with OS Windows).
- 2D and 3D visualization can be used.
- It is possible to turn and zoom the image and also to display level line in the image.
- The measure data can be exported to EXCEL or another program.

Plantograph measuring system can be used in various areas:

- In medicine (e.g.: orthopaedics; rehabilitation; prostheses and ortheses-development; biofeedback etc.);
- For the anatomy of sitting and leaning profiles design, especially in car and air-craft industry (by „crash-test“, air-back tests - being high demands on the dynamic mode of the transducer);
- In robotics (e.g.: for the stability and the robot-balancing point determination further for the grasp-force determination; the pattern recognition etc.);
- In any other industrial applications where is needed to know the pressure distribution on loaded area;
- In the sport medicine and methodology.

Plantograf measure system was awarded in 1998 by 1st price of Innovation in the Czech Republic and in 2005 by Certificate of meritn (second place in Price of Innovation in CR).

5.2.2 Sensor for stress field in bone

Parts of skeleton are changing their qualities during human life. These changes are joined by re-modeling the structure which influences the stress field in the bone material. The option how to estimate them is to use transducers.

Principal of the transducer (developed on author's workplace) is given by the distribution of stress field round cylindrical hole [36] and [37]. As it is not possible to measure these stresses directly, a transducer has to be inserted into the examined bone. But the rigidity of the embedded transducer must not influence considerably the stress field. From the medical reasons outer diameter of the hole cannot be greater than 3 mm.

Problems of biological compatibility and aseptic treatment (potential application of the transducer in the bone is 6 - 8 months) have predetermined material used for injection needle. Theoretic and numerical calculations were performed so that optimal distribution of the examined stress field in the bone was received. The outer diameter of the elastic body of the transducer is 2,5 mm, wall thickness 0,2 mm, total length according to medical demand was 6 mm (Fig. 31).

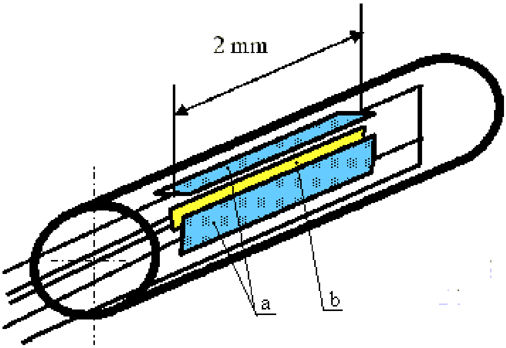


Fig. 31 Design of transducer

As it was not possible to apply train gages in the circumferential direction the only chance was to apply semi-conductive strain gages axially orientated (Fig. 31). First tests were done with semi-conductive gages available on market which had greater length (3 mm) than was needed. Last version of transducer has length of strain gages only 2 mm. These tests proved great sensitivity to asymmetric positioning of the transducer and to the geometrical position of the transducer in the bone. Fig. 32 shows placing of sensor in bone.

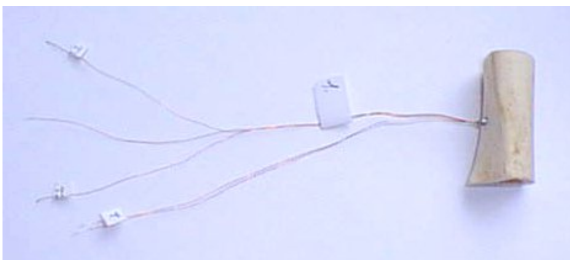


Fig. 32 Placing of transducer in bone

Results of testing measurement are presented in Fig. 33.

According to our request the domestic producer VTS/SGT Zlín produced for us shorter base of the strain gage (2 mm) and applied one pair of the above mentioned gages on the inner surface in a halfbridge connection. This transducer does not suffer any longer from additional influences (non-symmetry, bending, temperature shifting).

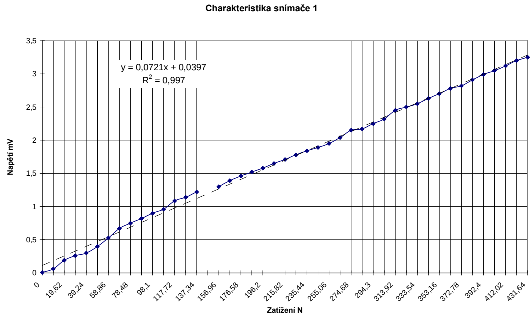


Fig. 33 Measured characteristic of transducer

Special attention was given to strain gage insulation which has to fulfill requirements of biocompatibility as well as resistance at sterilization by temperature, chemicals or radiation.

5.2.3 Measure of pressure distribution in knee joint replacement

The measurement was done in the knee joint replacement produced by a firm Walter a.s. Such a model of knee replacement didn't comprehend lattice ligaments and didn't accurately correspond to a physiological knee joint.

In this model we used only stress of tibia-femoral contact area with pressure which was three times of body weight. Medium body weight of one person is approximately 70 kg and we used stress 2 100N. Math model [34] pressure distribution on tibial plateau is shown on Fig. 34.

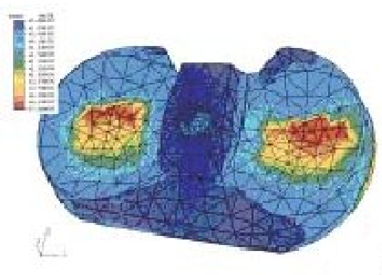


Fig. 34 Math model

Sensors are allocated in maximal pressure area by model [38]. Gaps are made to the tibial plateau and sensors are fixed in it, see Fig. 35. The gap is limited by elastic area of tibial plateau (material UHMWPE). This is important for validating results. Placement of sensor is parallel with axis of gap. The sensor is sealed in the wall of the gap and it ensures that the sensor will be vertical aligned. The sensitivity of the sensors is maximal in this case. After fixing of sensors the gap will be filled with polyethylene material. The count of gaps is limited by their diameter (R = 3 mm) and depth 6 mm. When the count of the gaps is bigger, the geometry and also the course of tension in tibial plateau are changed. We decided to make four gaps to the tibial plateau. In three gaps there is only one sensor and in the last gap there are two sensors: one is for the measurement of stress and the second is for the compensation of temperature influence on the measurement.

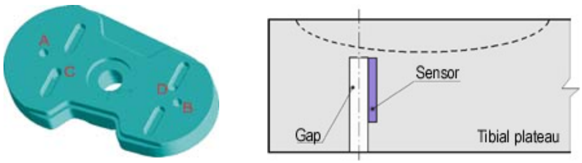


Fig. 35 Placing of sensors

We chose semiconductor strain gages for our measurement. Their characteristics were advantageous for us. We used single crystallic semiconductor tensiometer with conductivity N length of 2 m from manufacture VTS Zlín. These tensiometers were developed specially for author's workplace. Measure device Spider 8 of firm Hottinger HBM was used for the measurement. Calibration was made by cooperation of Department of Mechanics, Biomechanics and Mechatronics of Faculty of Mechanical Eng. of CTU in Prague.

Until now first stage of the measurement has been realized. In this stage static pressure was measured in selected angles (flexes) between femoral component and tibial plateau. The pressure was measured by this way: for selected angles action force was increased and decreased on knee joint replacement in range 0 - 1730 N. Full measurement was realized on device which is able to simulate moving in knee joint replacement. The measured results in gap D are presented on Fig. 36

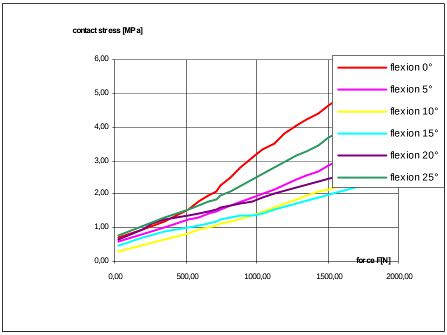


Fig. 36 Force F contact and angle stress dependence
(strain gage in gap D)

5.2.4 Transducer for occlusion measurement

A special transducer for occlusion measurement was developed for this measurement. This transducer was developed on author's workstation of Faculty of Mechanical Eng. of CTU in Prague [35]. This transducer is based on conductive elastomer and derived from design PMT 1.4 sensor. Dimensions are 12 x 9 mm and the design is presented on Fig. 37 in two variants. For transducer the areas are oriented opposite of molar top. The loading response for one transducer area is presented on Fig. 38.

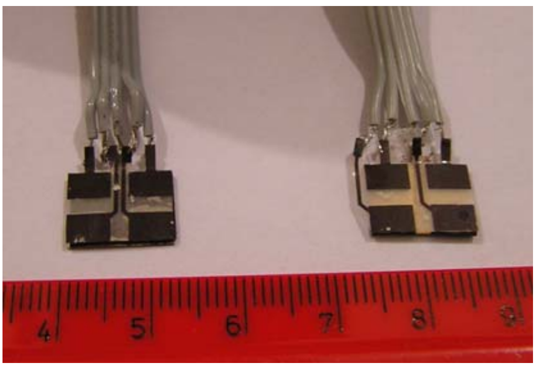


Fig. 37 Design of occlusion transducer

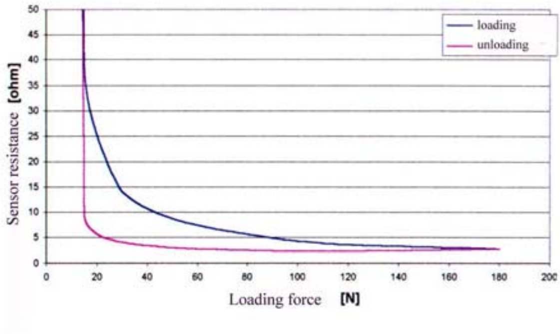


Fig. 38 The loading response

5.2.5 Otto Bock hand replacement

On the web sites of firm Otto Bock [53] the human hand SensorHand™Speed replacement of their own production can be seen. This hand is controlled by EMG signals in hand stub. Control system enables proportional control of gripping force in the range 0 – 100 N and proportional speed griping speed in the range 15 – 300 mm/s. This hand enables to catch a subject that flies, e.g. in sports. This hand is equipped by sensors and a function AutoGrasp, which enables gripping force to increase by gripped object slip.

The hand construction is shown on Fig. 39 its final design on Fig 40.

Fig. 39 Construction of human hand SensorHand™

Fig. 40 Design of Replacement

5.3 Smart textiles

Smart textiles present another possibility for scanning of tactile information and its processing. A notion, what is it a smart textile, is very various. We can meet with several variants. In first line they are electronic elements that are integrated to clothing (see Fig. 41), e.g.

pocket mobile phone. Another kind is conductive textiles, which have different electronic element integrated. The textiles serve as wires in this case. Full functional units create e.g. display, keyboard, others possibilities are, see Fig. 42.

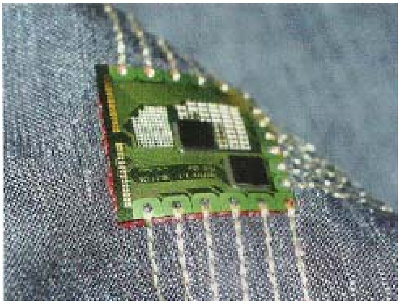


Fig. 41 Electronic elements connection on textile

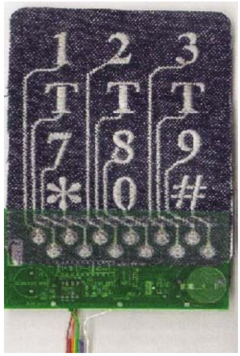
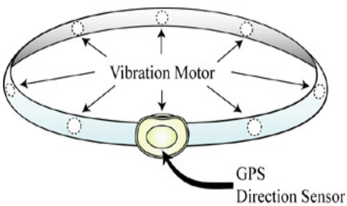


Fig. 42 Keyboard from textile

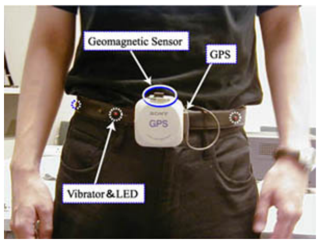
These technologies evolve and improve for commercial using. In this time commercial Wealthy system exists. It is the monitoring system for monitoring basic life function, which is integrated to clothing.

5.4 Tactile information as addition information source

Tactile information can be used by handicapped people as additional source, too. Fig. 43 a) shows a vibration belt for blind people [54]. The belt is connected by module GPS. The user sets a terminal address. The direction for the way is determined by vibration of the engine. The real system is shown on Fig. 43 b).



a)



b)

Fig. 43 Belt vibration system

5.5 Non-traditional tactile information using

Tactile information is used in other areas, in which we wouldn't expect it, more in [47] and [52]. Tactile information is used by aerodynamic tests of different objects, e.g. airplanes construction or by testing right of top rank skiers poise, see Fig. 44, or bikers, see Fig. 45. On these exhibits circumfluent air creates pressure on surface of the subjects. This pressure corresponded with relevant circumfluence.

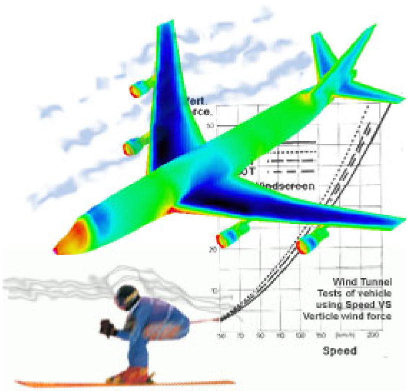


Fig. 44 Using of tactile information
by airplanes aerodynamic

Fig. 45 Using of tactile information by bikers aerodynamic

6 Conclusion

This contribution described basic tactile sensors and the principles, which can be used for force measurement in robotics, especially in biomechanics and other areas.

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CURRICULUM VITAE

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Czech Technical University in Prague, Faculty of Mechanical Engineering
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Education:

1973-1978	Czech Technical University (CTU) in Prague, Faculty of Electrotechnical Engineering, specialization: Control Systems
1981	PhD. of Technical sciences, branch: Technical Cybernetics, Faculty of Electrotechnical Engineering
2001	DrSc. technical science, CTU in Prague
1989	Assoc. Professor for branch Electrotechnics in Mechanical Engineering
1998	habilitation Assoc. Professor for branch Technical Cybernetics

Science experiences:

1994	invitation on Instituto Politechnico de Castelo Branco in Portugal in frame of TEMPUS grant (3 weeks)
1996-1998	head of grant of GACR (Grant Agency Czech Republic) No.:106/96/0953: „Scanning pressure distribution on sole for diagnostic in medicine and biomechanics“
1999-2004	co manager of GP CEZ J04/98:212200008 „Development of Methods and Instruments of integrate Engineering“
1999-2004	co manager of GP CEZ J04/98:210000015 “Research of New Methods for Measurement Physical Values and its Applications in Instrumental Techniques”
1999-2004	co manager of GP CEZ J04/98:210000012 „Transdisciplinar Research in Area of Biomedical Engineering“.

1996-1999	head of grant of GACR No.:106/00/1464: „Methods of direct Identification of Inside and Outside Mechanic Interactions of Human Locomotive Apparatus“
2003-2005	head of grant of GACR No.:106/03/0464 “Biomaterials and Contact Interface – Detection and Stress Analysis”
2005-2007	co manager of grant GACR 102/05/H032 „Research, Developing and Optimalization of Measuring Systems and Measures Uncertainty Evaluating by their Using in practice
2005-t.t.time	co manager of research project MSM 6840770015 „Research of methods and systems for measurement of physical magnitudes and measure data processing“

Lectures:

Electrotechnics 1 and 2
Technical Measurements (for bachelor)
Technical Measurement Engineering for foreign students
Special Sensorics
Electrical Measurements of physical Magnitudes (PhD study)
Control Theory 1 a 2 (branch Automatization on TF CAU)
Automatization Control of Technology Processes (branch Automatization on TF CAU)
Automatization Control of Technology Processes (PhD study on TF CAU)

Branch: tactile sensors and transducers for automatization, robotics, medicine and biomechanics, methods of pattern recognition of tactile information, microprocessor systems, control systems

Awards: Award of Year Innovation 1998 (1st award), 2002, 2004 appreciation of research collective by Czech Technical University rector, 2003 silver medail Faculty of Mechanical Engineering, Technical University Košice, Honorable mention Year Innovation 2005 (2nd award), 2007 Who’s Who insignia awardee

Publications: 92 articles published in national journals or conferences, 106 articles publicized in international journals or conferences, 48 research reports, 30 patents and patents registration, 5 appeal to lectures abroad, 4 appeal to lectures domestic

Activities: president of National Committee IMEKO, member of General Council of IMEKO, member of International Committee IMEKO TC 17, member of Presidium Czech Federation Science - Technical Societies (to 2007), Science secretary of CFSTS (to 2007), member of Cybernetic Association of Science Academy of Czech Republic, has been included to monograph Who's Who in the World 16th edition, International Directory of Distinguished Leadership – Millennium Edition and Who is who in Czech Republic

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