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Implementation of Microsensor Interface for Biomonitoring of Human Cognitive Processes

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1. Introduction

Miniaturization of biomedical sensors has increased the importance of microsystem technology in medical applications, particularly microelectronics and micromachining. This work presents a new approach to biomedical monitoring and analysis of selected human cognitive processes. The system is based on our preliminary described theory and experiments (Vavrinsky et al. 2010). We are primarily interested in biomonitoring of human cognitive processes and psychophysiological conditions of car drivers in order to enhance road safety.

Actually often used method is evaluation of abnormal car driver actions (sudden changes of direction with no direction indicators or too hard cornering). Main disadvantage of such a system is that they offer no prediction. More effective are prediction systems, which offer enough reaction time before undesirable situations, and so they can minimize human error factors and improve road-traffic safety.

Our present research is focused on sensing, processing and analysis of selected physiological signals for mental and medical condition recognition. They are known some studies describing interface between emotional condition and physiological responses, and we want also present some, since new ideas and research in psychological recognition and biomonitoring are very welcome. It is also proved that human decisions and reactions are affected by emotional and physical comfort. Emotional reconnoiter of a car driver conditions is influenced by many cognitive processes, such as mind organization, vigilance, planning or fatigue. Nervous and angry people can be very dangerous for traffic road safety.

In our experiments, we have monitored:

- psycho-galvanic reflex (PGR) – skin conductivity changes,
- heart rate + electrocardiogram (ECG),
- body temperature,
- respiration frequency,
- emotions.

To improve the reliability of our measurements, these parameters have been monitored often by duplicate methods, sometimes at macro level, sometimes by local microsystems technologies. In first step, we implemented our technology to the virtual reality driving simulator but preparations for real implementation have been already started, and the final car implementation will follow.

Two following experiments were performed:
- Divided Attention "DA" experiment - psychological monitoring of human cognitive processes,
- Car Driver Monitoring System "CDMS" – biomonitoring on a car simulator.

Both experiments are similar, since they are based on several common principles. Preliminary psychological experiment was focused on monitoring of selected psycho-physiological parameters (vigilance test, memory test, alcohol influence) possibly useful in road-traffic safety, and achieved results were applied in the following experiment "Car Driver Monitoring System".

2. Developed multipurpose microsensor

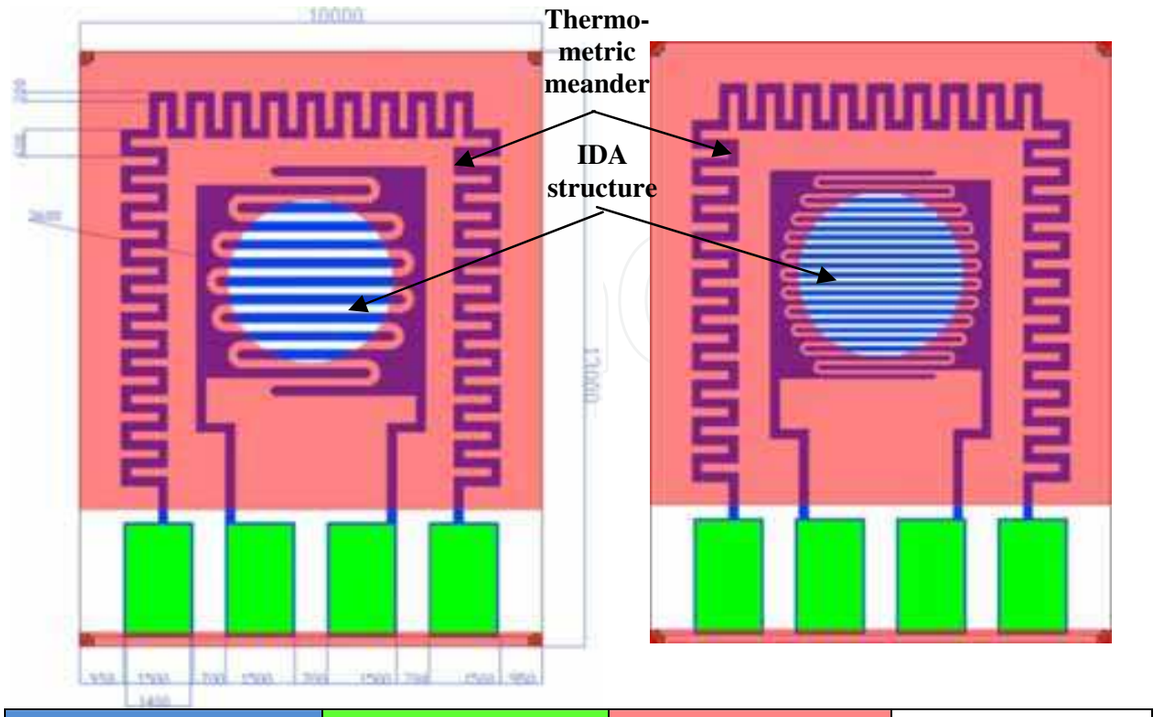
Successful development of high integrated and miniaturized electronic instrumentation and sensors needs to overcome a wide dimension-scale of mezo-micro-nano structures. This leads to the convergency and complementarity of microsystem technology and nanotechnology, and it demands an interdisciplinary scientific/technical collaboration also in basic research. Thin films serve as both: the source of new compound materials (particularly in optoelectronics) as well as well-defined and reproducible micro-/nano-interfaces between sensing, recognition and bio-chemical-physical-electrical transductions of signals in sensors (Tvarozek et al. 2007).

From electrical model of IDA (interdigital array) microelectrode/skin interface and simulations, the important outcome has arisen: the electric field distribution and depth of penetration into the outer skin layers (epidermis laminar structures) depend mainly on the configuration and size of an electrode system (Ivanic. 2003). This knowledge provides the possibility to examine different layers of epidermis by electrical impedance method, and this was used for the analysis of electrophysiological processes in the human skin when a person is under the stress influence.

Recently, new thin microsensors (IDAT), depicted in Fig. 1, have been developed, where:
- an interdigital array (IDA) of microelectrodes is integrated together with
- temperature sensor (T) on a single chip.

The developed microsensor allows measurement of psychogalvanic reflex (PGR) by IDA structure and body temperature by T meander, locally from "one place". Moreover, it can be found in previous experiments on the heart rate monitor. Therefore, the microsensor allows continual monitoring and analysis of complex physiological, pathophysiological, and therapeutic processes.

The microelectrodes were fabricated by a standard thin film technology: Pt (Au) films (150 nm in thickness) underlaid by Ti film (50 nm) were deposited by rf sputtering on Al_2O_3 substrates, and microelectrodes were lithographically patterned by lift-off technique. However, in electro-optical research, transparent conductive oxide of ZnO doped by Al (ZnO:Al) can be also utilized (Tvarozek et. al., 2007). The total size of the microelectrode chip is 10 x 13 mm. IDA structure was made in symmetric configuration: 100 μm / 100 μm and 200 μm / 200 μm (finger/gap) dimensions. Total resistance of thermal resistive meander by using Pt is between 530 and 540 Ω. Pt thin film is used to minimize the polarization effect. In all experiments described later, 200 μm / 200 μm symmetric structure was used.



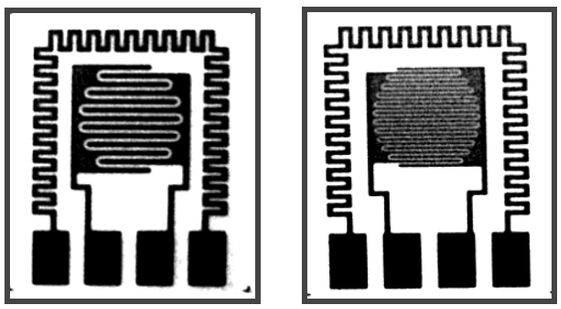
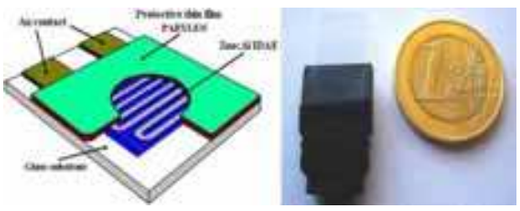


Photo snapshots



Transparent thin films technology - ZnO:Al

Fig. 1. IDAT microelectrodes

3. Divided attention experiment

Presented experiment was carried out in the laboratory of cognitive processes at Department of Psychology, Comenius University, in cooperation with Department of Microelectronics, Slovak University of Technology. This experiment has been performed on a group of 63 probands (all university students) in age between 18 and 29 (average = 20) years (48 female, 15 male). The experiment was focused on analysis of relations between cognitive processes, psychophysiological correlatives and human personality parameters at different activation levels. Secondarily, we have mapped also relations of psychophysiological correlatives to emotional reflex (face mimic) and alcohol intoxication (Fig. 2).

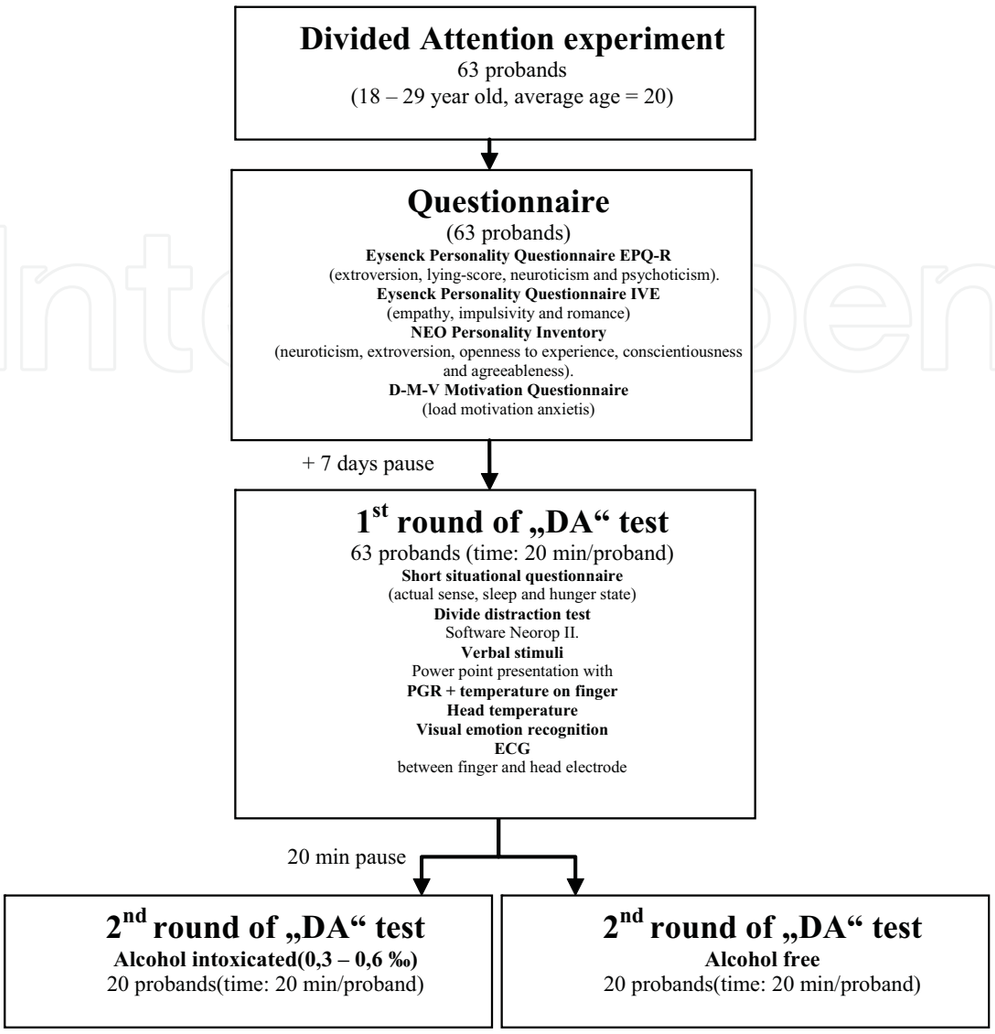


Fig. 2. Divided Attention experiment

Divided attention "DA" test was separated into three rounds:

- Questionnaire,
- 1st round of "DA" test, and
- 2nd repeat round of "DA" test with alcohol influence monitoring.
  - (Blood alcohol concentration: 0,3 – 0,6 ‰)

Each round of the "DA" test itself was divided into four time phases:

1st – Relaxation time (3 - 4 minutes): self concentration, relaxation music, etc.

2nd - Advice listening (3 – 5 minutes): listening to spoken words

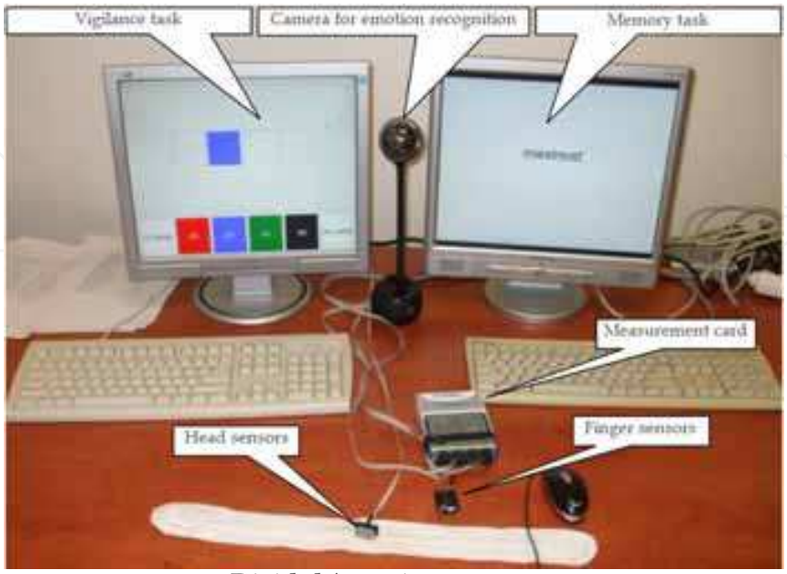
3th – Distraction stress (5 - 6 minutes): solving two tasks at same time:

- Vigilance task:
  - Software Neurop II – SPEED test (measurement of reaction time - image and sound stimuli). (Gaal. 2002)
- Memory task:
  - Power Point presentation with verbal stimuli (numerical tasks and words remembering (10 negative, 10 positive, 10 neutral types of words)).

4th – Memory task (2 minutes): Writing of remembered words from 3th phase.

3.1 Technical set-up

The complete measurement set-up used in "DA" experiment is depicted in Figure 3. The developed IDAT sensor was first used in "Divide Attention" psychoexperiment.



Divided Attention test set-up



Detail of NI 9219 with sensors

Fig. 3. Divided Attention test – measurement equipment

During this cognitive test, four electro-physiological parameters were monitored:

- psychogalvanic reflex (PGR) and body temperature sensed by the designed IDAT integrated microsensor on the ring-finger of non-dominant hand,
- head temperature sensed by a standard Pt100 sensor,
- Electrocardiograph (ECG) sensed between head and the ring-finger.

Additionally, the face mimic representing different psychological emotions were recorded by a camera (Logitech, 2009), and visually recognized and diagnosed using software "eMotion" (eMotion, 2009). "eMotion" was designed in "ISLA Laboratory at the Universiteit van Amsterdam" for real-time visual (face mimic) emotional recognition. The program allows recognition of these emotions, "Neutral", "Happy", "Surprise", "Angry", "Disgust", "Fear" and "Sad", from saved video files or online video source (camera).

Experiment was controlled by a personal computer (PC) with new programmed software "Psychoprogram" (Fig. 4). "Psychoprogram" was designed in Labview 8.6 environment, and has built up software interfaces for the camera, "eMotion" program and NI 9219 measurement card with sensors. NI 9219 has measured resistances from IDAT sensor (PGR + temperature),

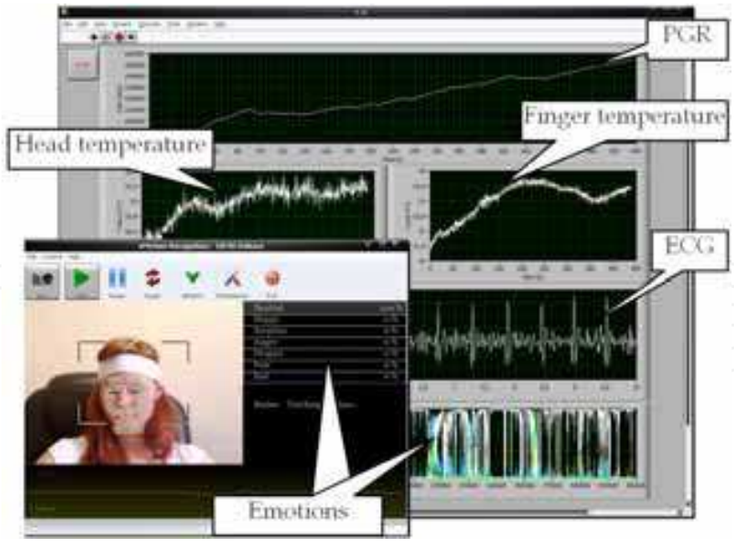


Fig. 4. Divided Attention test – Control computer print screen

resistance from Pt100 head sensor and ECG voltage at 100 samples/s and 24-bit resolution (Fig. 3 bottom). For ECG signal we applied software IIR Bandpass filter (Cutoff frequencies: 7 - 40 Hz, Order: 7, Topology: Bessel). Other signals were only resampled down to 2 S/s.

3.2 Results and discussion

The achieved results have confirmed several previously obtained observations (Vavrinsky et. al, 2010), shown in Fig. 5:

- The psycho-galvanic reflex causes a change of the skin impedance during periods of stress, excitement or shock. Under these conditions, skin conductivity increases, whereas during periods of relaxation the conductivity declines to a minimum (Olmar. 1998, Weis et al. 1995, Brezina. 2007)
- Psychological activation results in human body temperature decreasing and increasing of the skin conductivity (PGR) at the same time.
- The amplitude of a particular parameter depends on the stress activation level, and it is individual for each proband.
- The temperature response shows also more integral character.
- Activation phase of the parameters' response is followed by the relaxation phase.
- Memory task (4th phase of "DA" test) decreases the body temperature more significantly than observed for phases 2 and 3.
- The conductivity (PGR) in 4th phase is decreasing in contrast to phase 2 and 3.

In 3rd phase of "DA" test - "Distraction stress" (activation) phase the following observations were registered:

- Heart rate grows up approximately by 11 beats, in comparison to 1st relaxation phase. This result observed for all probands is very reliable (Fig. 6).
- Visual emotions are changed from "Neutral" emotion in 1st phase to "Happy" or "Angry" emotions in 3rd phase. The intensity of "Happy" and "Angry" emotions is more than doubled (Fig. 7). We also found that emotion "Angry" can by often reflected as "Concentration" emotion, which was not reckoning in "eMotion" software.
- Emotion "Disgust" corresponds to faster reaction times in "Vigilance task".
- Emotion "Fear" causes increased heart rate.
- Sleepiness from questionnaire decrease total performance in "Vigilance task".

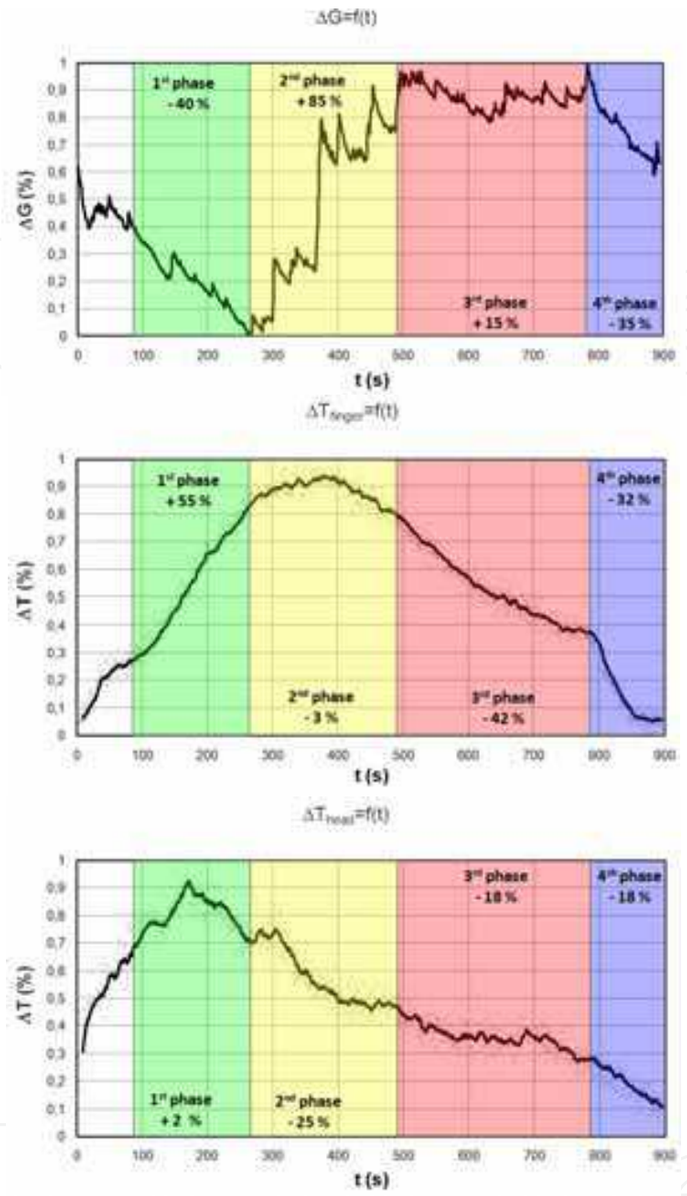


Fig. 5. Conductivity and temperature results of "DA" Test over respective phases (typical example)

In 2nd round of "DA" test we divided 40 probands in 2 groups to monitor alcohol influence on test effectivity and heart rate changes.
We had:

- 20 slightly alcohol intoxicated probands (0,3 – 0,6 ‰),
- 20 normal probands.

They are existing scientific findings, that alcohol has negative influence on learning and memory processes. Principally alcohol decrease remembering of new information. The visual memory falls rapidly, but semantic memory is not influenced. The efficiency of recognition tasks decrease, even though the number of right answers is increased, but the accuracy falls rapidly (Nociar. 1991, Snel. 1999).

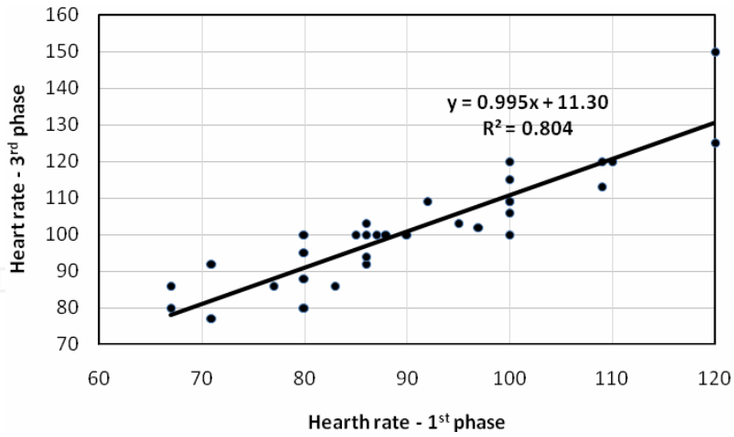


Fig. 6. Divide Attention test – Increasing of the heart rate in distraction stress

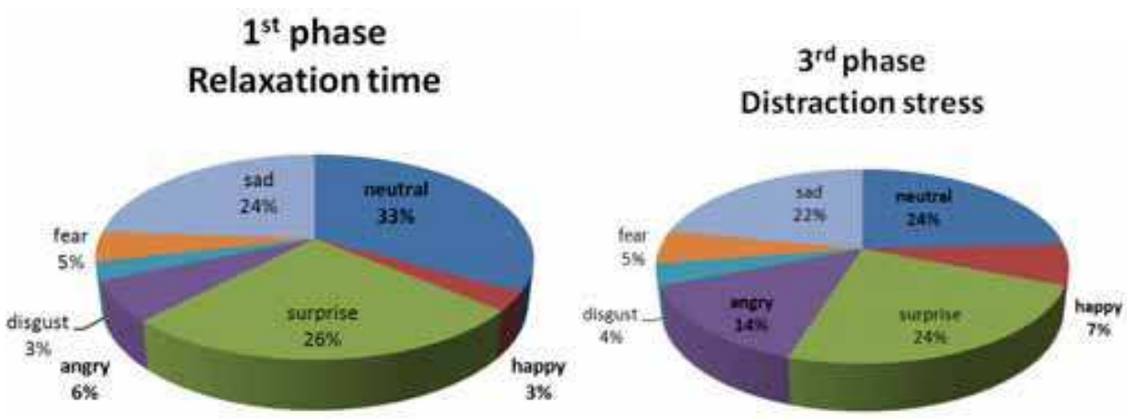


Fig. 7. Divide Attention test – Emotion changes

It is also known: If alcohol concentration in blood is in range 0,3 – 0,5 ‰ (our case), the probands are more relax, open - mind, self-confidence, but motoric reactions are slower. On 1‰ concentration start decreasing of sensor and talking functions and some people are more aggressive or retiring and crabbed (Atkinson. 2003).

We found that in 2nd round of "DA" test:

- Probands perform better than in 1st round, which is caused by better preparation on repeated task.
- Slightly "alcohol intoxicated" probands can achieve better results in vigilance task (3rd phase of distraction test), however, in memory task (4th phase) their performance was worse compared to "alcohol free" probands (Fig. 9). The difference was +7 % in vigilance task and – 3 % in memory task. The result corresponds to literature knowledge (Snel. 1999, Nociar. 1991).
- Heart rate of slightly "alcohol intoxicated" probands decrease comprised to normal state (Fig. 8). The literature knowledge was verified.
  - We calculated formula for alcohol intoxication influence on heart rate:

    Alcohol intoxicated heart rate = 0,63 * Normal heart rate + 29,5

  - For more precise formula estimation is possible to perform experiments with variable values of alcohol concentrations in blood.

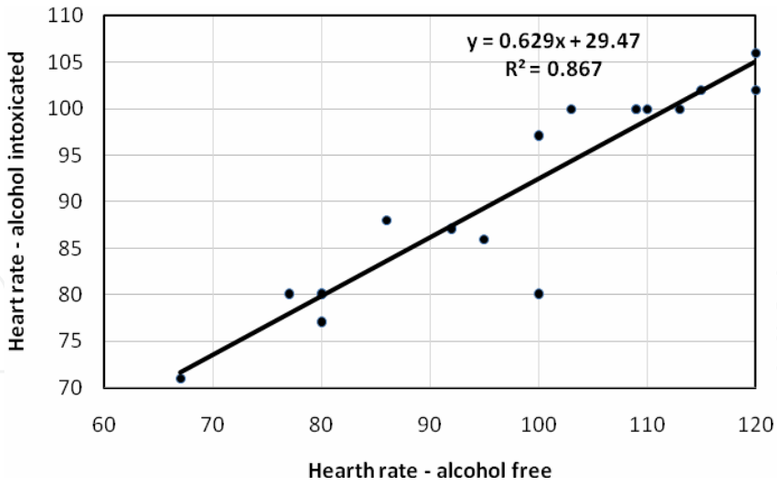


Fig. 8. Divide Attention test – Decreasing of the heart rate under alcohol intoxication

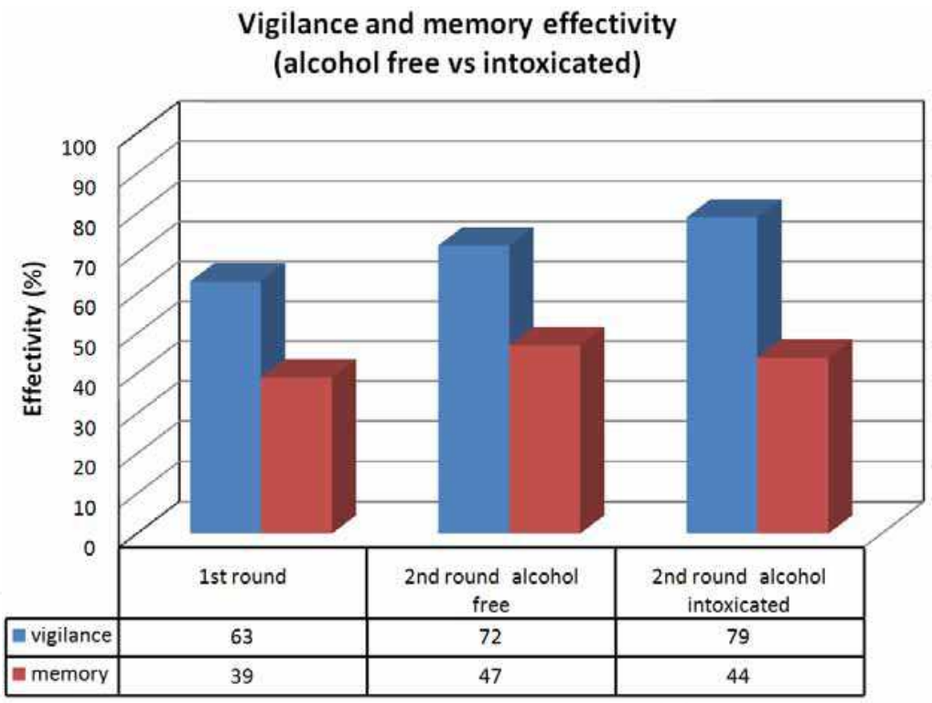


Fig. 9. Divide Attention test – Influence of alcohol intoxication on vigilance and memory

4. Car driver monitoring system

Obtained results and tested set-up configurations of "Divided Attention experiment" were used in next "Card Driver Monitoring System" (CDMS).

4.1 Technical set-up

The proposed and designed Car Driver Monitoring System (CDMS), depicted in Fig. 10, consists of:



Fig. 10. Car Driver Monitoring System (CDMS)

- 2 local micro PGR + temperature (left and right hands)IDAT sensors on a driving wheel
- 1 global macro PGR sensor and 1 global macro ECG sensor for monitoring of conductivity and ECG between left and right hand placed on driving wheel
- 1 smart pressure sensor, placed in the driver seat, for heart rate and respiration frequency monitoring (Partin et. al, 2006). It can be partially used for the driver weight measurement too.
- The system also includes an infrared (IR) modified camera with several tested optical filters to minimize shadows and glitters in real conditions, for visual emotion recognition. The camera can be also used in the eye position system or in the safety system for driver identification.
- "Compact RIO system" (National Instruments, 2009) controlled by NI Labview 8.6, with implemented mathematical apparatus for signal processing, filtering and analysis:

- NI 9263:
  - 4-Channel, 100 kS/s, 16-bit, ±10 V, Analog Output Module
- NI 9219:
  -24-bit, 100S/s, Ch-Ch Isolated Universal Analog Input Module (±125 mV to ±60 V, ±25 mA, TC, 3 and 4-wire RTD, ¼, ½, and Full-Bridge)
- NI 9203:
  -8-Ch ±20 mA, 200 kS/s, 16-Bit Analog Current Input Module
- NI 9234:
  -4-Channel, ±5 V, 51.2 kS/s per Channel, 24-Bit IEPE
- 12 VDC power supply

- Control PC with camera software connected over RJ45 net

The design of measurement unit is based on the modular programmable automation controller CompactRIO (NI 9014), low-cost reconfigurable control, and acquisition system designed for applications that require high performance and reliability. The system combines an open embedded architecture, small size, extreme ruggedness, and hot-swappable industrial I/O modules. Because we want to make a low-cost final product, finally, only a classical web-camera, not high precision cameras or thermal cameras will be used, and the final electronic part of the system will be placed on a single board.

4.2 Results and discussion

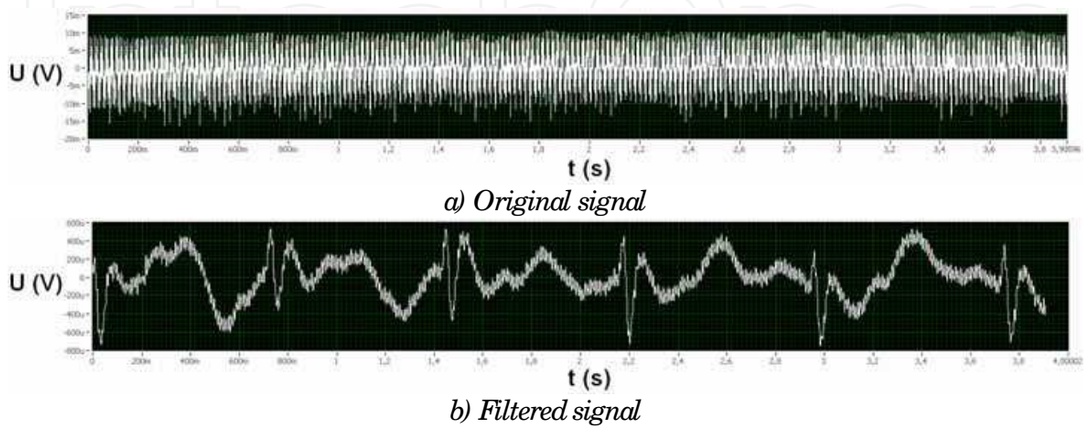
4.2.1 Driving wheel sensors

4.2.1.1 ECG and PGR by macroelectrodes

For global monitoring of ECG and PGR by driving wheel we used:

- Aluminum macro electrodes
- ECG electrodes were connected to NI 9234.
  - Sample frequency: 25,6 kHz (can be reduced to about 100 Hz)
  - Software IIR filters:
    -Bandpass filter: (Cutoff frequencies: 1 - 130 Hz, Order: 10, Topology: Bessel)
    -Bandstop filter: (Cutoff frequencies: 48 - 52 Hz, Order: 10, Topology: Bessel)
- Conductivity (PGR) electrodes were serial connected to NI 9263 (±10 V Analog Output Module: V_{OUT} = 3V, f = 1 kHz) and NI 9203 (Analog Current Input Module, Sample frequency: 100 Hz)

Typical result for ECG monitoring is shown in Fig. 11.



a) Original signal

b) Filtered signal

Fig. 11. ECG signal from a driving wheel

The PGR response of macroelectrodes (skin conductivity) corresponds to typical signal of commercial PGR sensors like in old results (Vavrinsky, 2010).
Macroelectrodes offer very fixed contact between human skin and electrodes and the total reliability is very good.

4.2.1.2 PGR, body temperature and heart rate by multipurpose microsensor

In this set-up we used multipurpose IDAT microelectrodes (Fig. 1) placed up on driving wheel and connected to NI 9219 card (Sample frequency: 100 Hz).
Electrical experiments led to a very important result: the developed microelectrode probes are able to monitor PGR, temperature as well as heart rate simultaneously. The PGR and temperature output signal corresponds to preliminary experiment (Fig. 5) and the heart rate was easily read out by derivation of the measured skin conductivity waveform (Fig. 12).
Standard psychotests also showed that the response signals of IDAT microelectrodes and macroelectrodes were similar. IDAT microelectrodes signals were more stabile with shorter response time, but for better reliability in real praxis, we need to place microsensors on several positions of driving wheel – to obtain more fixed contact.
In real praxis is ideal to combine macro and micro-sensors results.

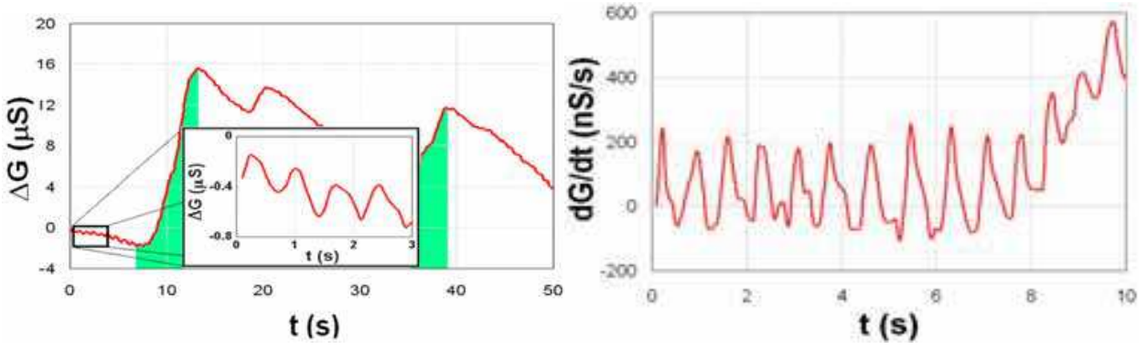


Fig. 12. CDMS – Heart rate by IDA microstructure

4.2.2 Seat sensor

For biomonitoring seat sensor was proved. In this set-up, the pressure sensor Treston DMP 331 converts mechanical (pressure) force from air filled seat cushion (modified medical pressure cuff XXL) (Medihum. 2008) to the output current that is then, measured via a serially connected National Instruments 9219 card (24-bit, 100 Hz sample frequency). As power supply we used 12 DC batteries. Treston DMP 331 is a smart sensor with the following features (Treston. 2010):

- Hybrid integrated technology
- Pressure range 0 – 0,6 bar
- Output current 4 - 20 mA
- Input voltage 12 - 36 V
- Excellent long service life and linearity
- Negligible temperature effect on output signal
- Long service life
- Gas and liquid pressure measurement

Typical measured signal is shown in Fig. 13a. Period designated as T_{heart} corresponds to heart pulse signal, and period $T_{respiration}$ corresponds to the respiration frequency. For better

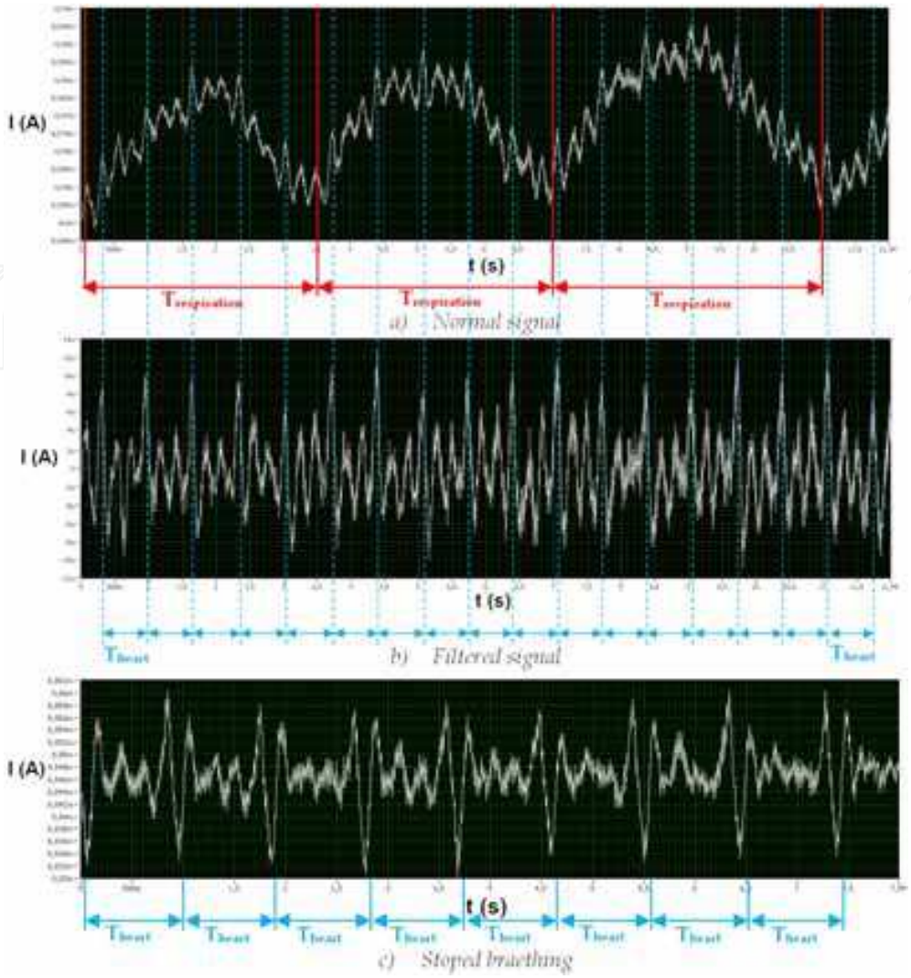


Fig. 13. Heart pulse and respiration frequency measured by the seat sensor

readability and reliability of heat rate, we can use mathematical filter IIR Highpass filter (Topology: Butterworth, Cutoff: 700 mHz, Order: 7) implemented in LabView (Fig. 13b). Fig. 13c shows output signal if you stop breathing.
Additionally, this system can be used also for measurement of a driver weight and then, his/her identification. We tested also fill seat cushion with water, but there was significant difference to air filling.

4.2.3 Visual emotion recognition

For visual emotional recognition we used like in first "DA" experiment cameras and eMotion software, but to improve reliability in real conditions (daylight, night), and to minimize the influence of unwanted optical effects like shadows and reflex from the outer sources, we used an infrared (IR) modified (active method) and thermal camera (passive method).

4.2.3.1 Active method

In first method (Fig. 14), to keep cost of the system down and make the system widely shareable, we have modified web camera for near IR spectra (0,8 – 1,3 μm). In front of the camera, optical filters to filter the visible light have been placed.



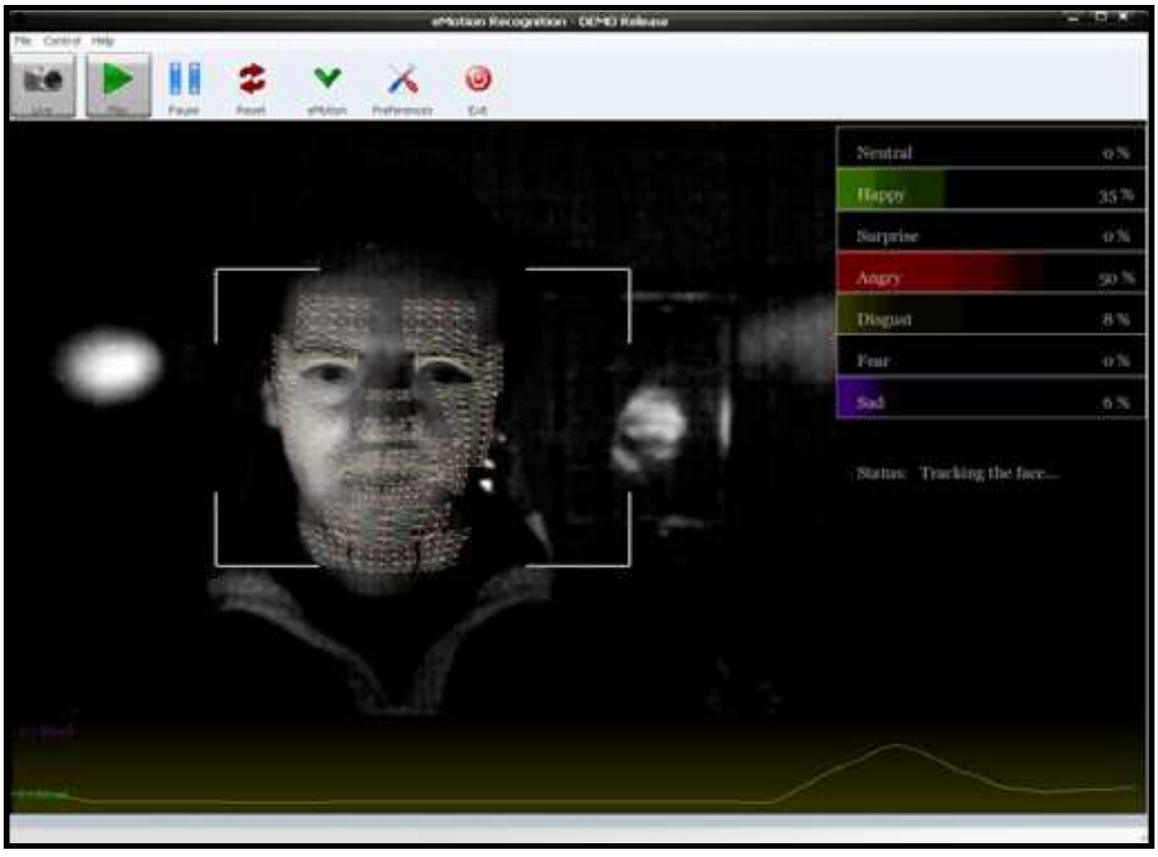


Fig. 14. CDMS - Active low-cost method of emotional visual recognition

Test set–up consist of:
- IR light source (λ = 880 nm)
- Camera: Logitech QuickCam® Orbit AF (Logitech. 2009)
  - Focused on a driver: With motorized tracking and autofocus, the spotlight is always on a driver's face, even when the driver moves around.
- Optical filters (Apollo Design Technology. 2008) (Fig. 15)
  - AP5300 - Apollo Green:
  - AP2330 - .9 Neutral Density:

Using this system we can read a driver mimic and obtain his/her real-time emotions in real road traffic conditions. The system of optical filters can be also easily modified.

AP5300

- Made of double coated, heat-resistant polyester
- %T = 4.4
- Pantone Match: 341
- RGB Match: 0 - 130 - 101
- CMYK Match: 100 - 0 - 67 - 29

AP2330

- Made of double coated, heat-resistant polyester
- %T = 12.7
- Pantone Match: 70% of black
- RGB Match: 109 - 111 – 113
- CMYK Match: 0 - 0 - 0- 70

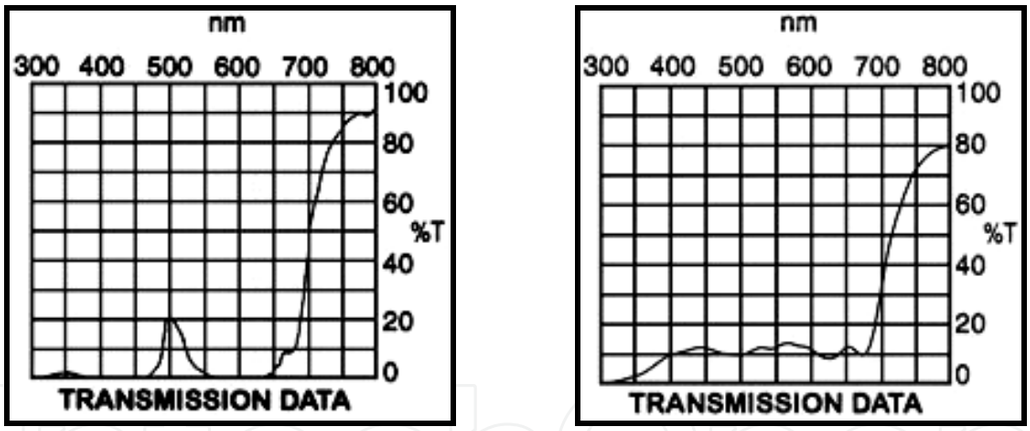


Fig. 15. CDMS – Transmission spectra of used optical filters

4.2.3.2 Passive method

In this set-up thermal camera EasIR 4 for far IR (8 - 14μm) was connected to a personal computer via S-Video (NTSC norm) input of AVerTV USB2.0 lite card. For visual recognition we used again eMotion software. This experimental equipment is not one of the low-cost versions, however, it can be additionally used for "contact-free stress monitoring for drivers divided attention" like in (Shastri et al. 2008). One disadvantage over previous active set-up is lower resolution of captured video (160x120 versus 1600x1200 pixels).

We found, that visual recognition software "eMotion" is able to work in near IR (B&W) (Fig. 14) and also in middle IR (Thermal) (Fig. 16) mode.

Thermal camera EasIR 4 - parameters (Guide Infrared, 2009):

- Detector Type: Microbolometer UFPA 160×120 pixels , 25μm
  Spectral range: 8 - 14μm

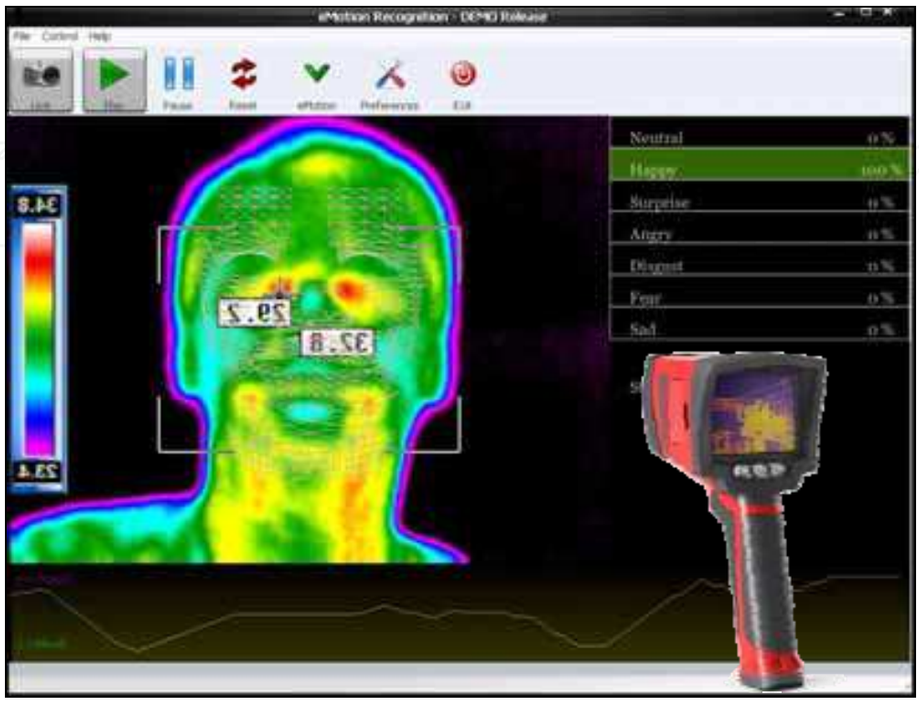


Fig. 16. CDMS – Using of passive thermal camera for emotional recognition

5. Next opportunities

Using of ZnO:Al materials for IDAT microelectrodes allows simultaneous optical (light reflectance of human skin in the 545 nm - 575 nm wave length ranges) and electrical (skin conductivity, temperature and heart rate) measurements. This method can measure the quantity and oxygenation of hemoglobin in top layers of the human skin (based on pulse-oximetry principle), that might offer another very important input factor in monitoring some psychosomatic processes. The advantage of the optical method is also in the contactless manner of monitoring, which is independent on the contact quality variations due to the possible physical activity of the respondent during testing (Vavrinsky et al. 2010).
Implemented camera can be used not only for biomonitoring of car driver psychical state. We can use traditional or skin texture analyzing face recognition (Bonsor et al. 2008) in car security system, where digital image of yourself, your face could replace your car key (password). They exists several free software products (KeyLemon. 2010, Banana Security. 2010).
One of the negative aspects of driving is also ”lack of events” on the road and instant driver’s drowsiness. To minimize this effect, a driver’s head, eye-lid and papilla movement might be sensed by a camera. Several software methods exist. The testing of these methods is prepared and will be included in our future experiments.
At last, car driver monitoring system can by enhanced by electromyography EMG analyzer, Doppler sensors for respiration frequency and driver movement measurement, or online alcohol sensors.

6. Conclusion

The achievements from „DA“ experiment were implemented into a driving simulator “CDMS”. Used set-up offers continuous biomonitoring and analysis of different electrophysiological aspects of human physiology in a completely safe and non-invasive manner. This technique also has no undesired influence on natural physiological processes. Motivated by the promising results achieved so far, the research will go on by the next step that is integration of the whole biomonitoring system into a real car conditions. We prove that ideal and reliable car monitoring system needs often using multiple measurements methods and the final product will need very robust and smart programmed analyzing software.

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