Constructing a Prototype of an Intelligent Article of Clothing with Active Thermal Protection

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The organization, construction, experimental development of the first prototype of an intelligent article of clothing with active thermal protection are described. The prototype has been protected by patent rights in Croatia and abroad. The results of the architecture of this kind of intelligent clothing, sensor system, microcontroller system, actuators and the rationalization of energetic resources of the power supply system are presented, together with the results of the integration of all the technical subsystems into an intelligent article of clothing with active thermal protection.
Key words: *intelligent clothing, active thermal protection*

1. Introduction

At the turn of the third millennium intelligent clothing has become a topic of broad discussions. In view of its properties, it is supposed to surpass by far conventional clothes. Intelligent clothing is constructed by integrating miniature electronic components, tiny nanotechnological sensors and actuators, communication elements and electronic computers directly into the textile materials and clothing respectively. In such a way the intelligent article of clothing is able to monitor constantly the conditions of the environment and of its wearer, and thus be able to adapt to the needs of the wearer optimally, matching the observed environmental changes. It can measure and analyze environment parameters, evaluate them via the integrated computer and make individual decisions by means of which the garment is adapted to the environmental conditions. Thus, contemporary intelligent clothing assumes an active character with the elements of artificial intelligence, as opposed to the conventional clothing, the character of which is primarily passive.

At the meeting of the Thematic Expert Group, TEG 6 **Smart Textiles & Clothing** within the European Technology Platform for the future of Textiles and Clothing, organized by EURATEX (European Apparel and Textile Organization) and held in January 20, 2006, 37 experts coming from all the European countries accepted the definition and characteristics of the term intelligent clothing. The experts agreed that three sets of instruments should be integrated into an intelligent article of clothing:

– sensors for measuring and information input which collect input information,
– processing unit for interpreting input information and making decisions (microcomputers, microprocessors or microcontrollers with accompanying programs), and
– output actuators for adapting the article of clothing and providing output information.

After the TEG 6 accepted the above classification, the second meeting was held in Bruxelles, 29th March 2006 within the Organization of the European Union EURATEX, when it was concluded that the new functional classification should be the main subject of investigations [1, 2]:

– sensors and measurements (of the body, the environment, within the textiles),
– actuators,
– data processing and storage,
– power supply system (generation, storage, rational distribution), and
– communication (within textile or technical systems integrated into clothing, with the textile or clothing wearer, textile/clothing - environment).

This classification and the investigation objectives specified at the meetings of the TEG 6 evaluated in the best possible way the right concept of the investigations performed and published [3-12] and patent protection of the intelligent article of clothing with active thermal protection which was made by a team of scientists of the Department of Clothing Technology of the Faculty of Textile Technology of the University of Zagreb.

2. Basic conditions of the consensual patent PK20030727

Up to now, the technology of clothing manufacture has not used the integration of electronic components, such as temperature sensors on and/or within an article of clothing, transducers, measuring amplifiers, assemblies and regulating systems into the clothing with the aim of automatic thermal protection. Based on the authors' conceptual solutions, the research team at the Department of Clothing Technology, Faculty of Textile Technology, University of Zagreb, consisting of **D. Rogale, S. Firšt Rogale, Z. Dragčevć, G. Nikolić** and technician **M. Bartoš,** have decided to design an intelligent article of clothing with thermal protection. It has been constructed on the basis of the acquired knowledge and preliminary investigations, thus changing the state of technology in this field. Patent application was submitted to the State Intellectual Property Office of the Republic of Croatia. The title of invention is **Intelligent Article of Clothing with Active Thermal Protection** designated **HR P20030727 A2**, Fig. 1 [13].

The most distinctive patent claims in the patent applications are:

- Intelligent article of clothing with active thermal protection **identified as** having several independently controllable air sealing chambers, temperature sensors, pressure sensors, miniature compressor with pneumatic electrovalves and computer or microcontroller system.
- Intelligent article of clothing with active thermal protection according to claim 1 **identified as** having shoulder air sealing chamber, breast left and right air sealing chamber, back air sealing chamber and waist air sealing chamber which, when inflated, have sealing properties that do not allow the air circulation from the space between the body and the garment, and in case that the air seal-

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(54) **INTELIGENTNI ODJEVNI PREDMET S AKTIVNOM TERMIČKOM ZAŠTITOM**
INTELLIGENT ARTICLE OF CLOTHING WITH AN ACTIVE THERMAL PROTECTION

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(57) Inteligentni odjevni predmet s aktivnom termičkom zaštitom ima brtvene komore s prigrađenim cjevčicama kroz koje se može upuhivati stlačeni zrak. Kroz cjevčicu (1) napuhava se ramena brtvena komora, kroz (2) lijeva, a kroz (3) desna prsna brtvena komora. Kroz cjevčicu (4) napuhava se leđna, a kroz (5) pojasna brtvena zračna komora. Svaka komora ima svoj senzor tlaka stlačenog zraka, ramena senzor (6), prsna (7) i pojasna (8). O tlaku zraka ovisi debljina brtvene komore i njezina brtvena svojstva. Stanje termodinamičkih parametara unutar odjevnog predmeta mjeri se senzorom (9), a okoliša senzorom (10). U ovisnosti o odnosima parametara unutar i izvan odjevnog predmeta donosi se odluka o debljini brtvenih komora, a time i o termoizolacijskim svojstvima odjevnog predmeta koja se postiže promjenama tlaka zraka u komorama. Neaktivirane komore omogućuju maksimalnu cirkulaciju zraka i hlađenje tijela, a aktivne komore onemogućuju cirkulaciju zraka i tzv. efekt dimnjaka. Dodatna termička svojstva mogu se postizati i različitim kombinacijama aktiviranih i neaktiviranih brtvenih komora na istom odjevnom predmetu.

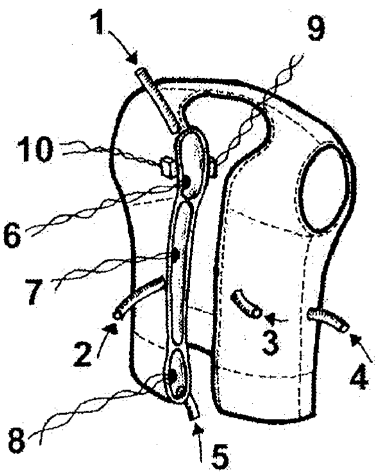

Fig.1 Original patent application published in The Croatian Intellectual Property Gazette, March 04, 2006

ing chambers are deflated, they allow the maximum air circulation, the so-called chimney effect.

– Intelligent article of clothing with active thermal protection of claim 1 **identified as** the thicknesses of air sealing chambers being regulated so that pneumatic electrovalves inflate air into the air sealing chambers using a miniature compressor, while the pressure sensors, in each sealing chamber one sensor, measure the pressure which matches the obtained sealing properties of the air sealing chambers or when insulation properties should be reduced, the air sealing chambers are to be deflated.

– Intelligent article of clothing with active thermal protection of claim 1 **identified as** containing sensors and the system for measuring environmental temperature and temperature between body and garment. Based on the ratio of the measured temperatures the computer or microcontroller system should make decisions on the necessity of inflating or deflating the sealing chambers in order to disable or to realize the optimum air circulation by activating different combinations of the air sealing combination, thus obtaining active thermal protection.

Patent application was also submitted in 2004 to WIPO, under the same title and by the same applicants [14]. On the basis of the patent application submitted June 12, 2004, the document on a consensual patent was granted (Fig. 2).

REPUBLIKA HRVATSKA
DRŽAVNI ZAVOD ZA INTELEKTUALNO VLASNIŠTVO

ISPRAVA
O KONSENZUALNOM PATENTU

Na temelju Zakona o patentima ("Narodne novine", broj 78/99. i 32/02.) proveden je postupak kojim je utvrđeno da su zadovoljeni svi propisani uvjeti za priznanje, te se priznaje

KONSENZUALNI PATENT
PK20030727

za izum:

INTELIGENTNI ODJEVNI PREDMET S AKTIVNOM TERMIČKOM ZAŠTITOM

Nositelj(i):
Dubravko Rogale, Snježana Firšt Rogale, Zvonko Dragčević i Gojko Nikolić

Izumitelj(i):
Imena izumitelja navedena su u Patentnom spisu koji je sastavni dio Isprave

Datum upisa u Registar patenata: 06.06.2007.
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Nositelj ima na teritoriju Republike Hrvatske zakonom utvrđena prava u trajanju od najdulje 10 godina, računajući od 11.09.2003. godine.

Cjeloviti podaci i opis izuma sadržani su u Spisu konsenzualnog patenta koji je sastavni dio Isprave.

U Zagrebu, 12. lipnja 2007.

UP/I-381-03/03-010/0727
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Ravnatelj
mr. sc. Željko Topić, dipl. oec.

Fig.2 The documents of the consensual patent

2.1. Sensors and systems of measuring input variables of the intelligent article of clothing

An intelligent article of clothing with active thermal protection should contain sensors of input variables in order to get information about the condition of its environment and the microclimate space between the intelligent article of clothing and human body, as well as the information about the pressures in the thermoinsulating chambers. In the case of the patent-protected intelligent article of clothing with thermal protection, five input variables are included:

1. environmental temperature of the intelligent article of clothing with active thermal protection (so-called external or ambient environmental temperature) - t_{out}
2. temperature inside the intelligent article of clothing with active thermal protection (so-called internal or microclimate temperature) - t_{in}.
3. pressure of the shoulder thermoinsulating chamber - p_r
4. pressure of the chest thermoinsulating chamber - p_p
5. pressure of the waistband thermoinsulating chamber - p_b

The intelligent article of clothing with active thermal protection experimentally designed has, in accordance with the representation of input variables, five sensors: two temperature sensors and three pressure sensors, as shown in Fig. 3.

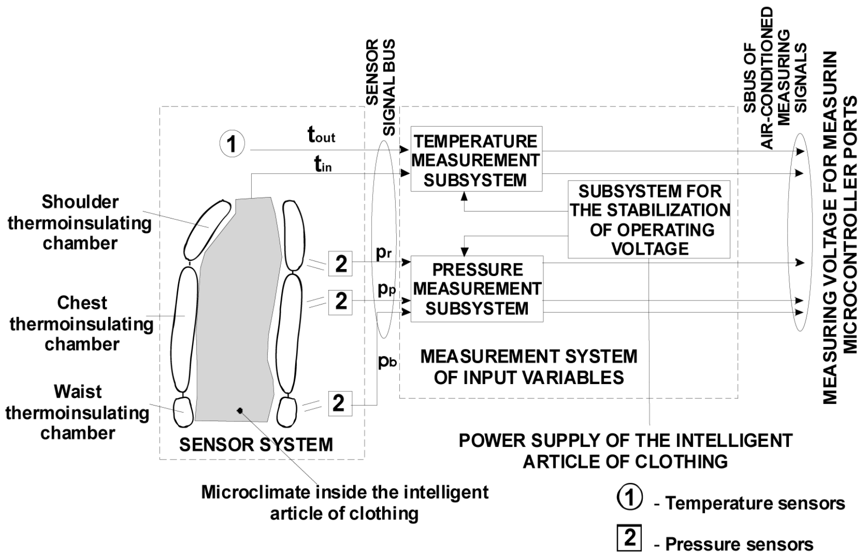


Fig.3 The sensor and measuring system of input variables of the intelligent article of clothing

Fig. 3 shows that the system of measuring input variable is composed of:

- pressure measurement subsystem
- pressure sensors within the thermoinsulating chambers
- measuring amplifier for pressure sensors
- temperature measurement subsystem
- temperature sensors for the microclimate space between clothing and environment and
- subsystem for the stabilization of drive voltage.

Air-conditioned and amplified measuring voltages of the input variables of the environment temperature and microclimate of the intelligent article of clothing, as well as the air pressure in the thermoinsulating chambers, are guided by **a measuring bus** to the microcontroller ports. A subsystem for the stabilization of drive voltage, necessary for the operation of the measuring system for input variables, is also included in the microcontroller system.

2.1.1. Pressure sensors in the thermoinsulating chambers

A RS235-5784 pressure converter made by RS Computers, USA, is used to measure pressure in the thermoinsulating chambers. The pressure converter dimensions are comparatively small, and it was selected because of its good properties, which made it possible to integrate it successfully into the intelligent article of clothing. The converter contains two ports for pressure measurement (port 1 and port 2), so it can measure pressure differences (differential manometer) or absolute pressure value.

The pressure converter can measure pressure up to 1 PSI, i.e. up to 68.95 mbar [15]. It permits a 20-fold overloading up to about 1.4 bar. The pressure sensor in the converter is a thin diaphragm, deformed with increasing pressure. Four piezo-resistors, changing their electric resistance according to the diaphragm deformation, are attached to it. The piezo-resistors are connected to a Wheatstone bridge.

Due to reduced voltage supply in the experiments conducted, sensitivity of 0.327 mV/mbar is reached and the highest output voltage from the measuring bridge of 22.55 mV respectively, at the highest pressure level recorded by the measuring converter.

The described output voltage from the measuring converter is too low to be measured by the microcontroller. This is why a moderate measuring amplifier of signals was constructed, to amplify the measuring signal about 200 times.

2.1.2. Measuring amplifier for pressure sensor

The power supply of the operating amplifiers presents a particularly demanding problem. In the development of an intelligent article of clothing with active thermal protection the power supply used is expected to be as small and as light as possible with as high a capacity as possible. If another voltage supply source with negative polarity was to be added, the development and construction would become more expensive and difficult, as well as the later usage of the intelligent article of clothing with active thermal protection.

This is the reason why a measuring amplifier with one positive power supply was developed, whereby the same battery-powered source is used which supplies the temperature measurement subsystem, microcontroller system and micropneumatic actuator system. Thus, a LM224N integrated circuit with four operating amplifiers, manufactured by renowned semiconductor manufacturers National Semiconductor, Motorola and Philips, is selected [16].

2.1.3. Temperature sensors of the microclimate space between the garment and the environment

The intelligent article of clothing with active thermal protection is devised in such a way that it can measure two significant temperature parameters: external temperature (or environment temperature) and microclimate temperature inside the garment. A measuring converter of the 3rd generation with digital processing measurement data designed DS18B20 by Dallas Maxim Semiconductors, USA, is selected for temperature measurements [17].

Its measurement accuracy is better than 0.2 °C, and the measuring range lies between - 55 °C to + 125 °C. The resolution of the integrated A/D converter can be adjusted between 9 and 12 bits, depending on the user needs. Each DS18B20 temperature converter has a unique and unchangeable mark integrated into a 64-bit serial number in the ROM memory of the converter, which serves as an address mark in the bus to which a practically unlimited number of measuring converters can be connected, each with its own address. They can all be connected to the bus which represents only one data conductor and mass (so-called "1-Wire bus"). The supply of the converter may be from 3V to 5.5V local DC source or via a data conductor (so-called "parasite power"). Conversion of the temperature data in the highest resolution of the 12-bit digital word lasts for 750 ms at most, and with the 9-bit one (lowest resolution) lasts for about 94 ms.

The energy consumption of the DS18B20 temperature converter is about 0.75 μA in sleep mode and about 1 μA in active mode.

The converter has three external ports: for serial data input and output by means of a single-wire bus for connecting the negative terminal of the voltage supply source and for connecting the positive terminal of the voltage supply source.

Inside the converter there are several circuits: for power supply over local source or in parasite mode over data bus, ROM memory with address data, data circuit, working RAM and EEPROM memory, temperature sensor, alarm circuits for too low and too high temperatures and a 8-bit CRC (Cyclic Redundancy Check) detection mechanism to make sure that the data has been read properly.

Thanks to a fully digital architecture of the measuring temperature sensor it is not necessary to design and build in analogous amplifiers of the measuring signals, as is the case with analogous pressure sensors.

2.2. Microcontroller system

Two microcontrollers are used to control the operation of the intelligent article of clothing with active thermal protection. Most of the functions, including the performance of the algorithm of intelligent behaviour, are controlled by a very powerful PIC 16F877, manufactured by Microchip, USA, and rational electric power management is controlled by a smaller-sized PIC 16F628 microcontroller of the same manufacturer [18].

The PIC 16F877 microcontroller has 40 connections on the box where a powerful central processing unit with RISC architecture (Reduced Instruction Set Computer) is located, so that it can recognize and perform 35 different computer instructions necessary for program processing. Its operation speed can be adjusted by changing the control frequency which can amount to 20 MHz. A FLASH program memory with the capacity of 8 kB, RAM data memory with 368x8 byte capacity and EEPROM data memory with 256x8 byte capacity is installed into the same box. Processing requirements can be addressed from 14 possible sources; it can operate in the so-called sleep mode or in the state of non-operation with reduced electric power consumption. It can operate with supply voltage ranging from 2 - 5.5 V, and at individual connections output current can reach up to 25 mA. Typical consumption amounts to 0.6 mA, with the supply of 3 V and the work cycle of 4 MHz. If work frequency is reduced to 32 kHz, with the same supply voltage, its current consumption amounts to only 20 μA. In the sleep mode, the consumption is less than 1 μA. The microcontroller described has three installed timers, two comparators, multichannel analogue-to-digital converters with a 10-bit resolution and the possibility of serial and parallel communication with its environment.

The smaller-sized microcontroller responsible for rational electric current consumption is located in the box with 20 leads into which the RISC processing unit as well as program and data memories are included. The FLASH program memory has the capacity of 20 kbytes, RAM data memory has the capacity of 224x8 bytes and EEPROM data memory has the capacity of 128x8 bytes.

Work frequency can also reach up to 20 MHz. Two analogue comparators and one source of reference voltage and a communication assembly are also built in. The microcontroller needs less than 2 mA with a supply voltage of 5 V and the work frequency of 4 MHz. At the reduced work frequency of 32 kHz, it consumes approximately 15 μA, and in the sleep mode the bias-current amounts to less than 1 μA. It recognizes and performs 35 program instructions.

Fig.4 The DR-4X2PN microcomputer manufactured by Clark

2.3. Actuator system

The actuator system uses micropneumatic elements. The basic system elements are: microcompressor for generating compressed air, electromagnetic valves for filling the air into the thermoinsulating chambers, electromagnetic valves for releasing the air from the thermoinsulating chambers, flexible hoses for compressed air, L and T plug-in connections and two-piece conical connectors.

Compressed air is generated by the DR-4X2PN microcomputer, with the dimensions of 25x50x66 mm and weighing 175 g (Fig. 4), manufactured by the Clark, USA. The microcomputer operates employing the diaphragm principle and is supplied with the direct current of 9 to 14 V, consuming 200 mA. Maximum work pressure of the microcompressor is 0.75 bar. The respective microcomputer can operate in any position, while the supply capacity of the compressed air is 4.5 l/min. All movable components of the microcomputer are located inside the protected box so that they cannot be damaged by the environment [19].

Electromagnetic valves manufactured by FESTO, GmbH, series Micro-Pneumatic, marked MZH-3-M3-L-LED (Fig. 5), are used to activate the supply of the compressed air into the thermoinsulating chambers. The electromagnetic valve is distinguished by its small dimensions, appropriate for the integration into the garment. The width of the electromagnetic valves is only 10 mm, input voltage is direct, with the value of 24 V. It offers maximum compressed air flow up to 80 l/min, is activated electrically, or alternatively manually. It has an integrated miniature LED which induces the activated state of electromagnetic valves. Working temperatures range from -5 to 50 °C, and the activation period is 13 ms [20].

Fig.5 The MZH-3-M3-L-LED electromagnetic valve manufactured by FESTO

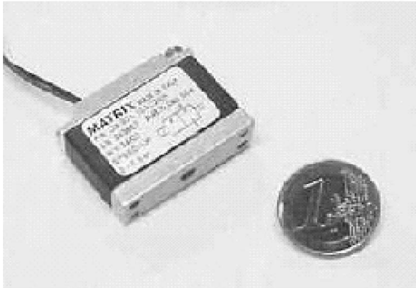


Fig.6 The 821 2/2 NC electromagnetic valve manufactured by Matrix

Electromagnetic valves made by Matrix, USA, and designated Matrix 821 2/2 NC (Fig. 6), are used to release the air from the activated thermoinsulating chambers. This type of electromagnetic valves is selected because of their very small dimensions and mass and a very high air flow. Their mass is 25 g, the air flow rate is 180 l/min, and the activation period is only 1 ms [21]. The thermoinsulating chambers with pressure converters are the part of the actuator system, and their description is given in the chapter 2.1.1.

2.4. Power supply system

A pack of rechargeable NiCd batteries with the total voltage of 24 V is used to supply sensors, microcontroller system and actuators. The battery pack consists of 5 sets of battery packages composed of 4 rechargeable NiCD batteries, each with the voltage of 1.2 V and the capacity of 1,200 mAh making total battery capacity 1200 mAh. The microcontroller monitors battery state-of-charge, and measurement results are constantly displayed. The actuator system is employed to ensure rational battery usage in the intelligent article of clothing with active thermal protection. During the period of the active operation of the garment, only minimum number of the elements of the actuator system, being energy users in the power supply system, are connected at the same time. The program support is conceived in such a way that the electromagnetic valves for inflating/deflating the chambers are activated sequentially, meaning that not more than one valve and microprocessor are active in the system at any particular moment [8].

Special system for activating and supplying the actuators in the system is used as another means of rational exploitation of the power supply system. It is constructed so that all the energy users are activated with their full operational voltage and starting current for the time interval of only several tens of ms in the first activation phase, while after the start up the so-called PWM (Pulse Width Modulation) supply is used in the second activation phase. This offers considerable savings of the supply system resources.

3. Experiment and results

The work on the entire architecture and functional operation of an intelligent article of clothing with active thermal protection began at the end of 2001, when a team of researchers at the Department of Clothing Technology, Faculty of Textile Technology, University of Zagreb, decided on a new research direction. The first thing to do was to search literature and to track the state of the art in the field. After published papers were investigated, the state of patent protection related to the clothing with various integrated technical systems was checked. In September 2003, after a comprehensive analysis and preliminary trials, the first patent application was submitted, in order to protect the original authors' solution of the intelligent article of clothing with thermal protection, described in the above chapters.

To construct an intelligent article of clothing with active thermal protection, following the patent application HR P20030727A, the whole architecture of the intelligent article of clothing with active thermal pro-

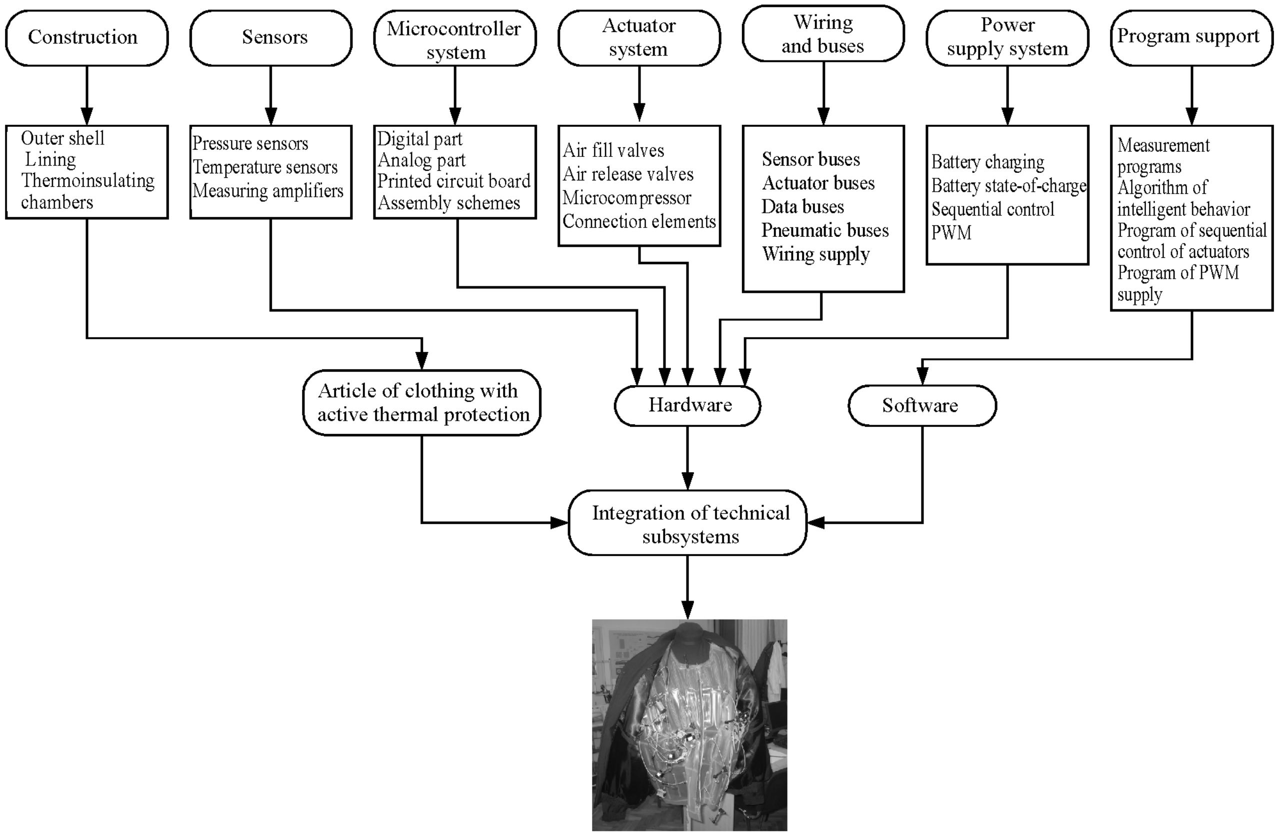


Fig.7 The architecture of intelligent article of clothing with active thermal protection

tection was studied. It consists of the following technical subsystems (Fig. 7):

– The system of the outer shell, of a programmable variable thickness, with an outer and inner protective fabric layers.

– The system of thermoinsulating chambers, offering the control of conduction and convection of body heat.

– Sensors and systems for measuring input variables.

A subsystem for measuring the temperature of the environment and microclimate of the article of clothing

A subsystem for pressure measuring in the thermoinsulating chambers

– The microcontroller measuring and control system for the intelligent article of clothing.

– The actuator system for the intelligent article of clothing with active thermal protection, with the elements of micropneumatics to control output variables.

– Power supply and

– A measuring and control program of the microcontroller with the algorithm of intelligent behaviour of the article of clothing.

The structure of subsequent investigations aimed at the practical construction of an article of clothing with active thermal protection was established, based on the specified architecture and technical subsystems. The structure of the experimental work and the assessment of the results in this paper were matched to fit the structure.

To manufacture the outer shell and the lining of the intelligent article of clothing with active thermal protection the model of a men's sports jacket (Fig. 8) was chosen. Special construction of the basic cut was designed for its construction and modelling. It can be applied to modelling all the models from which wear comfort and freedom of movement is expected.

Fig.8 The outer shell of the intelligent article of clothing with active thermal protection

A modification of the basic cut of a men's jacket model was made in order to integrate thermoinsulating chambers, the outer shell and the lining of the intelligent article of clothing with thermal protection were designed, the thermoinsulating chambers were constructed, while the functional dependence of the sample thickness of the thermoinsulating chambers at the maximum permissible pressure of 50 mbar and the changes in the width and length were determined.

Hereafter, the materials for the thermoinsulating chambers were chosen, and the most suiTab. methods of joining these materials were tested to make air-tight joints (seams).

By courtesy of Bayer Epurex Films GmbH, Germany, a few types of high-elastic polyurethane foils were delivered for the manufacture of thermoinsulating chambers. All the foils were subjected to extreme stresses and pressures. The foil designated Walopur 4201AU, with the thickness of 0.15 mm, the mass per unit area of 181.98 g/m^2, material density of 1.15 g/cm^3, softening point from 140 to 150 °C and very high breaking elongation, amounting to 550% [22] was selected. Moreover, the material was highly UV resistant, hydrolytically sTab., had good thermal and ultrasonic joining properties, and adequate microbiological stability, important for its integration into garments.

The measuring samples of the thermoinsulating chambers were sealed using the Pfaff 8310-003 Seamsonic ultrasonic welding machine. Polymer materials were welded by an ultrasonic circular sonotrode operating at the frequency of 35 kHz, and the ultrasonic vibrations were transferred to the rotating disc made of aluminium and titan alloy of 105 mm diameter 50 μm do 2 mm wide.

Fig.9 Pfaff airtightness tester

The gap between sonotrode and the anvil wheel could be varied with the accuracy of 20 μm using welding force from 0 to 800 N. The machine was equipped with a PC, to calculate and adjust the continuous density of ultrasonic welding energy at irregular welding speeds, whereby visual welding regularity strength of ultrasonic welding was obtained [23]. The welding parameters of the two foil layers designated as Walopur 4201AU were: gap between sonotrode and anvil wheel 0.31 mm, welding force 300 W and welding speed 0.43 m/min. Weld air impermeability was tested using a Pfaff air-tightness tester (Fig. 9), and it was found that the samples and welds were air-tight even after 24 hours at the constant pressure of 0.36 bar.

3.1. Investigation of thermoinsulating chamber construction properties

Investigations of thermoinsulating chamber measuring samples were conducted with the aim to find the regularity of changes in the dimensions of the thermoinsulating chambers when inflated. Eight different measuring samples of the thermoinsulating chambers were measured. Cumulative results of investigating the construction characteristics of the thermoinsulating chambers in a deflated or inflated state at a pressure of 50 mbar are given in Tab. 1.

The lengths and widths of the measuring samples of the thermoinsulating chambers in a deflated and inflated state and the height of the insulating chambers in an inflated state at a pressure of 50 mbar were measured.

Based on the data obtained, filling factors (f_i), contraction coefficients of measuring sample lengths in the inflated state (K_d) and contraction coefficients of measuring sample widths in the inflated state ($K_š$) were calculated [8].

Filling factor (f_i) represents the ratio of the height of the thermoinsulating chamber in the inflated state at the pressure of 50 mbar (h_k) and the segment of the thermoinsulating chambers (K_k). It is calculated according to the expression:

$$f_i = \frac{h_k}{k_k} \tag{1}$$

Contraction coefficient of the measuring sample length in the inflated

Tab.1 Cumulative results of investigating the properties of the thermoinsulating chambers

Sample no.	h_k (mm)	f_i	l_{ui} (mm)	l_{un} (mm)	K_d	$Š_{ui}$ (mm)	$Š_{un}$ (mm)	$K_š$
1	12	0,400	944	776	0,822	436	405	0,929
2	21	0,525	944	716	0,758	443	421	0,950
3	28	0,560	889	662	0,745	437	414	0,947
4	35	0,583	943	687	0,729	439	426	0,970
5	40	0,571	966	693	0,717	435	419	0,963
6	46	0,575	945	668	0,707	437	420	0,961
7	54	0,600	887	610	0,688	438	416	0,950
8	60	0,600	885	609	0,688	436	413	0,947

h_k- height of the chamber in an inflated state, f_i - filling factor, l_{un} - length of the sample in an inflated state, K_d - contraction coefficients of the lengths of measuring samples in an inflated state, $Š_{un}$ - sample width in an inflated state, $K_š$ - contraction coefficient of the width of measuring samples in an inflated state

state (K_d) is defined as the ratio of the sample length in the deflated and inflated state at the pressure of 50 mbar and is calculated according to the expression:

$$K_d = \frac{l_{un}}{l_{ui}} \quad (2)$$

Contraction coefficient of the measuring sample width in the inflated state ($K_š$) is defined as the ratio of the measuring sample width in the deflated and inflated state at the pressure of 50 mbar and is calculated according to the expression:

$$K_š = \frac{Š_{un}}{Š_{ui}} \quad (3)$$

Fig. 10 shows the graphic dependence of the thermoinsulating chamber height in the inflated state (h_k) at the pressure of 50 mbar on the chamber segments (K_k).

Regression analysis was used to determine that the height of the inflated thermoinsulating chambers (h_k) depending on the chamber segments (K_k) can be calculated using the following expression:

$$h_k = 0.667 \cdot K_k - 6.333 \quad (4)$$

Provided that the height of the thermoinsulating chamber in the inflated state, upon which thermoinsulation properties will depend, is given (h_k), the necessary chamber segment (K_k) can be calculated according to the following expression:

$$K_k = \frac{h_k + 6.333}{0.667} \quad (5)$$

Regression analysis was used to establish a mathematical expression appropriate to calculate the contraction coefficient of the measuring sample length in the inflated state (K_d), provided the segment of the thermoinsulating chamber (K_k) is known:

$$K_d = 0.841 - 0.002 \cdot K_k \quad (6)$$

Regression analysis was also used to provide a mathematical expression appropriate to calculate the contraction coefficient of the measuring sample width in the inflated state ($K_š$), provided the segment of the thermoinsulating chamber (K_k) is known:

$$K_š = 0.94 + 0.0001917 \cdot K_k \quad (7)$$

The investigation of the regularity of changes in dimensional characteristics of the thermoinsulating chambers are the basis for the design of the outer shell and an accepTab. appearance of the garment to be manufactured.

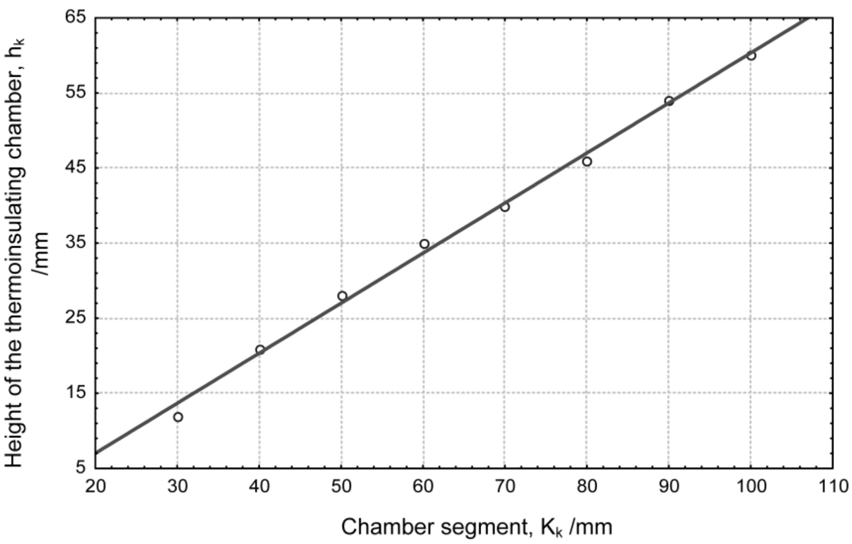


Fig.10 The dependence of thermoinsulating chamber thickness in the inflated state (h_k) at the pressure of 50 mbar in chamber segments (K_k)

3.2. Constructing the measuring system

The measuring amplifier of the pressure signal in the thermoinsulating chambers is composed of four operating amplifiers, housed in an integrated circuit designated as LM 224 and manufactured by National Semiconductor.

The measuring amplifier is supplied by the stabilized direct voltage of 5 V. It has four measuring channels, AN0 to AN3, to which the measuring bridges of the pressure sensor are connected. Short connectors JP3 to JP6 are used to select a branch of the measuring bridge, where the compensation of the maladjustment of the measuring bridge is made. Trimmer potentiometers R17, R19, R20 and R21 are used to compensate their maladjustment. Trimmer potentiometers R16, R18, R23 and R22 are used to set the amplify value of each measuring channel. The output signals from the measuring amplifier are guided to the JP1connector and are subsequently guided to the microcontroller board.

In contrast to the pressure sensors, which should be connected to the special measuring amplifier, the temperature sensors can be directly connected to the microcontroller via connectors. DS18B20 temperature sensor manufactured by Dallas Maxim Semiconductors, USA is connected to one connector, and it measures microclimate temperatures inside the intelligent article of clothing with active thermal protection. The same sensor, measuring environment temperature, is connected to the other connector. The sensors are connected to the stabilized voltage supply source of 5 V. BC547 transistors are used to activate their operation as well as to initiate temperature measurement. The initiation is introduced via the connected pins of the PIC16F877P microcontrollers for measuring microclimate temperature and environment temperature.

Hereupon a serial transfer of data on the temperature value from the microclimate sensors is made. When the microcontroller activates the measuring sensor of the environment temperature, a serial data transfer from this sensor into the inside of the microcontroller is made.

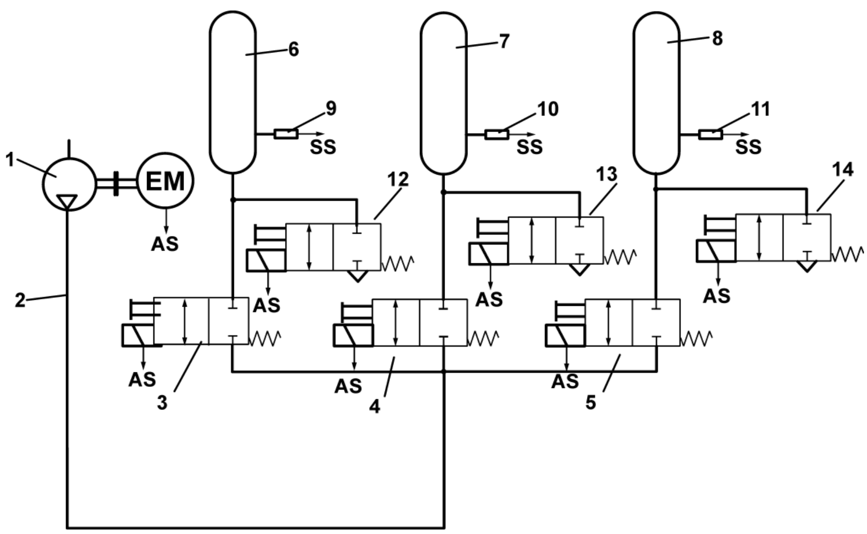
The results obtained in the experiments using the most suiTab. types of sensors for the construction of the intelligent article of clothing with active thermal protection show that the analogue pressure sensors require complex mechanical and electrical design, with special amplifiers of measuring signals. On the other hand, digital sensors are very simple regarding wiring and accompanying components.

Microcontroller programming is simpler when data are accepted from analogue sensors, and more complex when they are accepted from digital ones.

3.3. Constructing the actuator system

The operation of the intelligent article of clothing with active thermal protection is based on the activation of thermoinsulating chambers into which compressed air with the highest pressure of 50 mbar is filled. There are three groups of thermoinsulating chambers which are activated in different combinations, realizing different performances of the thermal protection of the garment. A system based on micropneumatic elements was therefore chosen as an actuator system in the intelligent article of clothing with active thermal protection. The system showing the best results in the operation of the intelligent article of clothing with active thermal protection is shown in Fig. 11.

The basic element of the system used for supplying compressed air is a DR-4X2PN microcompressor manufactured by Clark, USA, marked 1 in Fig. 11. Compressed air is guided via pneumatic tubing manufactured by FESTO, GmbH, Germany, designated PUN-4x0,75-BL and via L and T plug-in connections designated QSLM-1/8-4-100 and QSMT-4 to the electromagnetic valves 3, 4 and 5, which fill it into thermoinsulating chambers 6, 7 and 8. In such a way the electromagnetic valve 3, after being activated by the AS actuator bus (Fig. 11), lets the flow of compressed air into the shoulder thermoinsulating chamber 6. In a similar way the electrovalve 4 allows inflating the chest thermoinsulating chamber 7, and electrovalve 5 inflates the waistband thermoinsulating chamber 8. The RS 235-578 pressure sensors, made by RS Computers, USA, are connected in the thermoinsulating chambers to the thermoinsulating chambers. The signals coming from the pressure sensors are guided to the sensor bus SS, then to the amplifier of the measuring signals and to the microcontroller system. Particular thermoinsulating chambers are filled with compressed air after a decision has been reached, based on the algorithm of intelligent behaviour. The microcontroller activates the microcompressor 1 and at the same time one of the three air fill electrovalves 3, 4 or 5 of the associated thermoinsulating chambers 6, 7 or 8. During the operation of the microcompressor and the associated electrovalve, the pressure sensor constantly measures pressure value



Legend:

1	- DR-4X2PN microcompressor by Clark
2	- PUN-4x0,75-BL pneumatic tubing by FESTO
3, 4, 5	- electromagnetic valve for filling compressed air into the thermoinsulating chambers
6, 7, 8	- thermoinsulating chambers
9, 10, 11	- pressure sensors in the thermoinsulating chambers
12, 13, 14	- electromagnetic valves for releasing compressed air from the thermoinsulating chambers
AS	- actuator buses
SS	- sensor buses
EM	- electric motor of the microcompressor

Fig.11 The actuator system of the intelligent article of clothing with active thermal protection based on micropneumatic elements

in the associated thermoinsulating chamber. The microcontroller constantly monitors the level of the pressure, and when the value of 50 mbar is reached, the microcompressor deactivates the air filling electrovalve.

If it is necessary to inflate a particular thermoinsulating chamber, one of the air release electrovalves 12, 13 or 14 is activated (Fig. 11). The electrovalve 12 is used to deflate the shoulder thermoinsulating chamber 6; the electrovalve 13 is used to deflate the chest thermoinsulating chamber, and the electrovalve 14 to deflate the waistband thermoinsulating chamber 8.

If it is necessary to activate several thermoinsulating chambers, the program support provides a sequential activation mode so that at the same time only one chamber is filled with air, and only single air fill electrovalve and microprocessor are activated. Only after the first thermoinsulating chamber is filled, the sequential mode of inflating the other thermoinsulating chambers is started. During deflating the thermoinsulating chambers it is possible to activate several air release electrovalves at the same time, since the microcompressor, as energy user of heavier currents, has not been activated.

3.4. Constructing the power supply system

Experiments were conducted combining short activation of electrovalves with full voltages and currents lasting for several tens of ms, introducing series of PWM pulses afterwards, in order to ensure rational usage of the electric capacity of the battery assembly. The control method thus applied provided very interesting and original results shown through measurements by a digital memory oscilloscope.

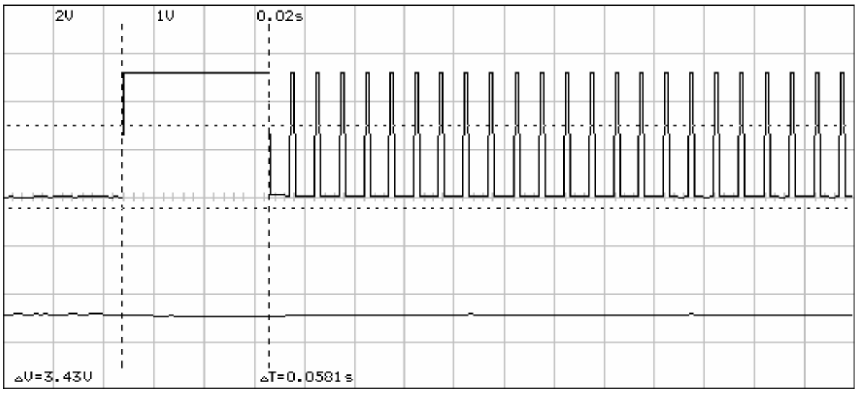


Fig.12 The oscillogram of the outlet for the auxiliary microcontroller used for the activation of electrovalves

Fig. 12 shows that the auxiliary microcontroller is switched on when the central microcontroller gives adequate command. It generates a pulse lasting about 60 ms at its exit (the first rectangular long-duration pulse). It is used to activate the electrovalves in full force, and a series of PWM pulses (a series of short wide-modulated rectangular pulses) follows afterwards in order to save energy.

Fig. 13 shows the oscillogram and the structure of PWM pulses. The left part of the oscillogram represents the end of the pulse for the activation of electrovalves in full force, while two starting PWM pulses in series can be seen on the right, the function of which is to keep the electrovalves in an activated state. The measurements indicated that, following the program, the PWM pulse lasted for 5 ms and that PWM pulses were renewed with a frequency of 200 Hz.

Fig. 14 shows the oscillogram with the voltage on the connectors of the electrovalve coil. The active part of

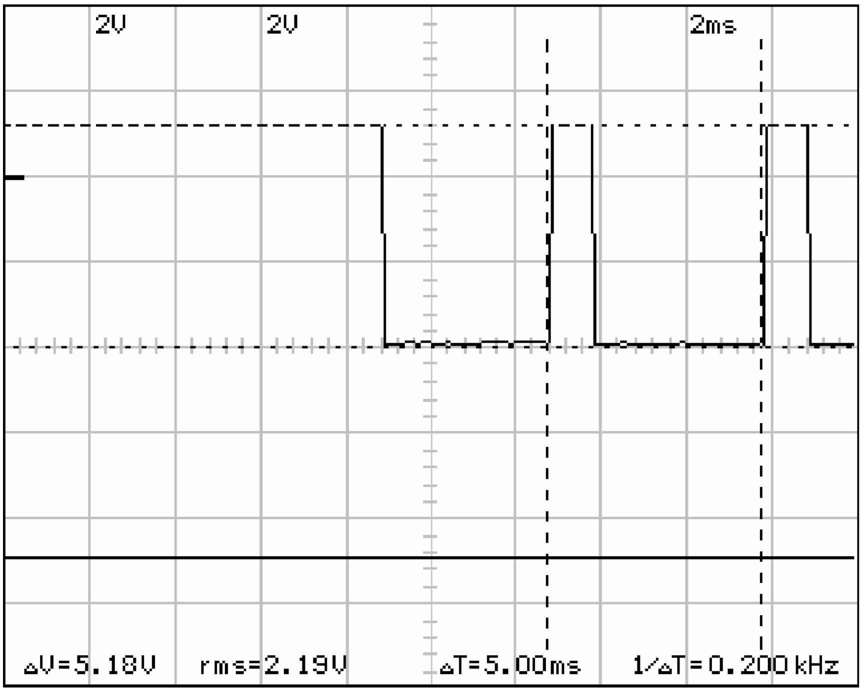


Fig.13 The oscillogram of the end of the activation pulse of electovalves in full force and the representation of the first two in a series of PWM pulses to keep electrovalves in the activated state with a reduced activation force

the PWM pulse, with total duration of 5 ms, lasted for 1 ms only, or 20%. The outlet was driven at 24 V, but due to the inductive character of the coil, the voltage from top to top of the pulse was about 27.2 V and was limited by the protection diodes. Since the active part of the PWM pulse lasted for 1 ms, we assumed that the electrovalve coil was activated and deactivated by the frequency of 1 kHz.

The oscillograms show that the time interval of only 60 ms is sufficient to activate the electrovalves in full force, and that the electrovalves can be kept in the activated state with the PWM pulses in the ratio of 1/5, compared to total duration. The second measuring cycle showed the following results:

The measurements of drive battery power consumption showed unexpectedly good results. Namely, the electrovalve at the voltage of 24 V consumed the current of 21.4 mA, meaning it needed the power of 0.514 W to reach activated state.

Measurements showed that when the activated electrovalve was kept by PWM pulses the stabilization current is only 1.8 mA so that it needs a power of only 0.043 W to be kept in an activated state.

Thus, when using the PWM modulated pulses, 12 times lower power was necessary than for the directly activated electrovalve, amounting to 8.4%. In other words, the resources of the drive battery foreseen for the control of the electrovalves could be used 12 times longer than the electric control without the PWM pulses.

It is expected that the reduction will be about 5 times, because the active part of the PWM pulses was 20% of the total duration (1 ms in relation to a duration of 5 ms), but it was obvious that the electrovalve coil was not only ohm resistance for direct current. It represented complex resistance of inductive impedance, proportionally high related to the frequency of the PWM pulses (200 Hz), and still higher from the aspect of the duration of the active part of the PWM pulses (1 kHz). This is the reason why the supply current of the electrovalve was lower than expected.

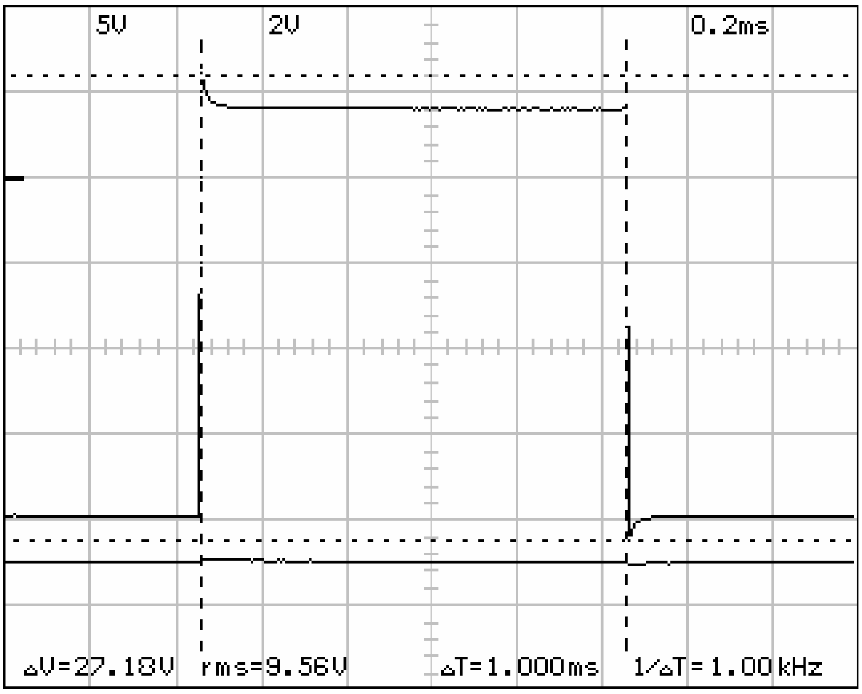


Fig.14 The active part of a PWM pulse with the total duration of 1 ms

Likewise, it was observed that the electrovalve directly supplied with a voltage of 24 V heated rather fast, while the electrovalve supplied with PWM pulses did not show any signs of heating up.

3.5. The integration of technical subsystems

Fig. 15 shows the results of the integration of all the technical subsystems. The first practical design of the prototype of the first intelligent article of clothing with thermal protection was done in accordance with the Croatian patent **HR P20030727 A2** and the international patent application **WO 2005/023029 A1.**

The basis of the technical subsystem integration is the shoulder, chest and waistband insulating chamber to which the printed circuit boards of the microcontroller system and the measuring amplifier for the pressure signal are attached. A group of conductors runs from the printed circuit board of the microcontroller system, while data display of the work parameters and actual state of the intelligent article of clothing with active thermal protection, sensors of microclimate and environment temperature, as well as other usual wiring to control the actuator system, are attached to it. The actuator system is connected by means of micropneumatic components. It consists of three air fill and three air release electromagnetic valves for the shoulder, chest and waistband thermoinsulating chambers and the microcompressor which supplies the system with compressed air. Fig. 15 also shows three groups of connection elements with pressure sensors in the shoulder, chest and waistband thermoinsulating chamber, as well as the connection of the microcontroller system with the external PC for programming the microcontroller and the control of its operation, the connection for the battery charging system and other auxiliary wiring form the subsystem. The integration of all technical subsys-

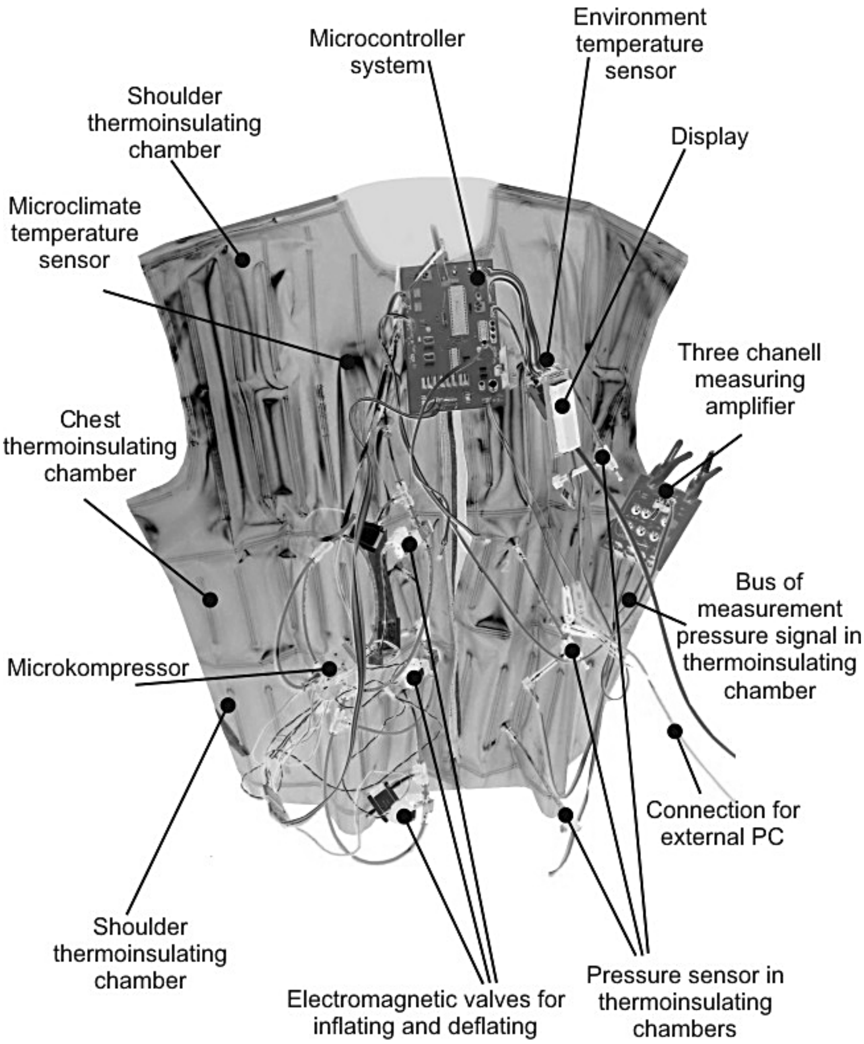


Fig.15 The result of the final integration of all the technical subsystems and the first practical design of the prototype of the first intelligent article of clothing with active thermal protection

tems allows for the article of clothing with active thermal protection operates to measure independently the environment and microclimate temperature in itself, to properly interpret the measuring data and to make decisions on the necessary response in terms of thermal protection and in line with the flowchart from the algorithm of intelligent behaviour. It independently carries out the decisions made by activating the microprocessor and other actuator elements and controlling their operation by means of the integrated pressure sensors. An independent and efficient operation of the intelligent article of clothing with active thermal protection is made possible through the described integration of all the technical subsystems.

Fig.16 shows actual design of the microcontroller system with the connected sensors of the garment environment and microclimate temperature. The circuit board houses the main microcontroller, the basic control program for the intelligent article of clothing with active thermal protection, the auxiliary microcontroller for the rational control of electric power systems and the integrated circuit for the serial com-

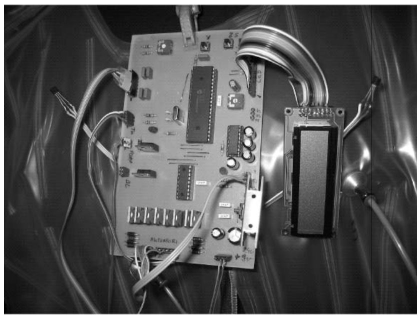


Fig.16 Microcontroller system with the connected sensors and display

munication with the external personal computer.

The integrated LC display for the communication between the wearer of the article of clothing and the microcontroller system can be seen as well. Figure 16 also shows a series of MOSFET transistors to control actuators and wiring parts of the intelligent article of clothing with active thermal protection.

Fig.17 shows the pressure sensor of the chest chamber, the connection connector and the two-piece conical connection element for the air duct. The pressure sensor is connected to the air duct made of highly flexible plastic tubing designated PUN-4x0,75-BL made by FESTO and a T plug-in connection designated OSMT-4 made by FESTO. The air duct is attached over the two-piece conical connection element to the thermoinsulating chamber so that the air pressure inside the chamber could be transferred to the pressure sensor. The voltage data in

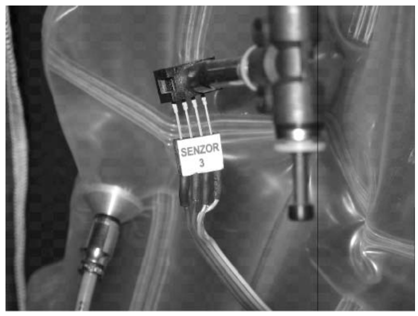


Fig.17 The pressure sensor of the shoulder chamber, connector and two-piece conical connection element for the air duct

the measuring bridge of the pressure sensor is transferred to the plug-in connector and afterwards via the signal bus of the measuring converters to the measuring amplifier of the pressure signal. There are two more fully identical pressure sensors n the prototype designed, intended for the chest and waistband thermoinsulating chambers.

Fig. 18 shows the fill and release compressed air electrovalves for the shoulder thermoinsulating chamber with a part of the air duct system and the T plug-in connection.

The FESTO electromagnetic valve is used to fill the compressed air into the thermoinsulating chambers, and the Matrix electrovalve to release the air from the chambers.

There are two more fully identical pairs of electromagnetic valves n the prototype designed, intended for the breast and waist thermoinsulating chambers.

Fig. 19 shows the DR-4X2PN microcompressor made by Clark, located under the thermoinsulating chambers and attached to the air duct of the micropneumatic system.

All the elements of the technical systems integrated into the intelligent article of clothing with active thermal protection are relatively thin, thinner than the thermoinsulating chambers.

Fig.18 The electromagnetic valves for filling and releasing compressed air into the thermoinsulating chambers with a part of the air duct system and the T-plug connection

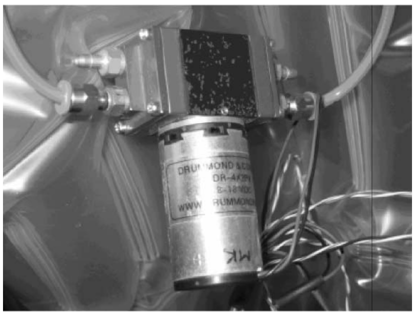


Fig.19 The microcompressor for inflating the thermoinsulating chambers connected to the air duct system

4. Discussion

While constructing the intelligent article of clothing with active thermal protection, measuring samples of the thermoinsulating chambers were tested. Appropriate air-tight and highly elastic material of a sufficiently low mass per unit area and air-tight joining properties was also tested. Likewise, the most appropriate methods of joining highly elastic foils of the thermoinsulating chambers by gluing, thermal joining using conduction and convection and ultrasonic welding were chosen. Optimum welding results were achieved on the ultrasonic welding machine.

Ten different types of thermonsulating chambers with different segments were constructed in order to investigate the behaviour of changes in the dimensions and thicknesses of the thermoinsulating chambers in the inflated as well as in the deflated state. Specially designed two-piece pneumatic elements were connected to the chambers. Measuring samples were tested using several micropneumatic components. It was found that the height of the inflated chambers was nearly linearly related to the changes in chamber segments (Fig. 10), and the factor of filling the chambers was almost constant. In practical use, it was around 0.55, meaning that the chamber inflating at the optimum pressure of 50 mbar is slightly higher than half of the segment of the thermoinsulating chamber (Tab. 1).

The contraction coefficient of the thermoinsulating chambers measuring sample length, in the inflated state, drops slightly, with the increasing value of the chamber, being in practice between 0.7 and 0.8. It means that the inflated chambers reach between 70 and 80% of their original length in the inflated state (Tab. 1).

After constructing the outer shell and thermoinsulating chambers the design, construction and experiments with the measuring systems for the input variables of the intelligent article of clothing with active thermal protection were carried out. Two technical subsystems for the environment and microclimate temperature measurement of the intelligent article of clothing with active thermal protection, as well as for pressure measurement in the thermoinsulating chambers were developed for this propose.

Analogue converters in a Wheatstone bridge were chosen for pressure measurements, and analogue measuring amplifiers with operating amplifiers and a cumulative measuring amplifier with four operating amplifiers were constructed for them.

Digital temperature converters were chosen for temperature measuring, and a measuring assembly with a microcontroller system was designed for them.

The experiments showed that third-generation digital measuring converters and conditioning measuring signals according to the DSSP (Digital Sensor Signal Processing) architecture exhibited exceptional characteristics during temperature measurements. The sensor generation should be used in future development of the intelligent article of clothing.

A microcontroller system with a single microcontroller was used in the first phase of the experiments with the intelligent article of clothing with active thermal protection.

As the requirements on the efficient processing of all the input variables and highly complex control of the technical systems integrated into the intelligent article of clothing with active thermal control increased, it was realized that powerful microcontroller versions should be used and that the microcontroller system should be based on the simultaneous operation of two microcontrollers. For this reason, the microcontroller system with one microcontroller was abandoned, and a new system with one basic and one auxiliary microcontroller was developed. A very powerful PIC 16F877 microcontroller made by Microchip was used for the environment, microclimate and pressure measurements in three thermoinsulating chambers, as well as to control displays and control keys and to produce the algorithm of intelligent behaviour. A slightly smaller-sized PIC 16F628 microcontroller, made by the same company, performed the tasks involved in the rational control of electric power. The main microcontroller communicated with the external personal computer via an MAX232 integrated circuit.

After constructing the microcontroller system the design, construction and experiments with the actuator system of the intelligent article of clothing with active thermal protection were carried out. In principle, the actuator system consisted of a microcompressor, three compressed air fill electrovalves, three compressed air release electrovalves, plug-in connections and other smaller elements necessary for connections to the thermoinsulating chambers. Chapter 3.4 and Fig. 10 show the block diagram of the actuator system which offered the best results in the experiments. The microcompressors and electrovalves are connected via buses to the board of the microcontroller system. The experiments indicated that that the microcontroller system could efficiently control the thermoinsulation properties of the intelligent article of clothing with active thermal protection. The dimensions of the actuator system elements were slightly larger than the elements of the sensor measuring system, but their mass still sufficiently small and appropriate to be integrated between the outer shell and the thermoinsulating chambers or the lining of the intelligent article of clothing with active thermal protection.

It should be emphasized that a new approach was made to the efficient and rational consumption of electrical power of the integrated batteries in the intelligent article of clothing with active thermal protection. For these purposes, well known experiences with the PWM control were applied. As a novelty, two modes of rational energy consumption from the integrated batteries of the intelligent article of clothing were used. This is the so-called sequential control, meaning that at a particular moment of the actuator system control, a minimal number of the elements of the actuator system is used, i.e. in the case of need several thermoinsulating chambers can be inflated sequentially, one after the other, and not all at the same time, which would increase the consumption of electrical power, and the efficiency of inflating the thermoinsulating chambers as well. Another novelty is the usage of the actuator approach for the complex PWM control, consisting of two series of PWM pulses. The first in the series of pulses lasts for about 60 ms (the first rectangular long-duration pulse), and is used to activate the electrovalves in full force. Afterwards, a series of PWM pulses (a series of short wide-modulated rectangular pulses) are used to save energy. All the knowledge acquired by conducted experiments resulted in the integration of all the technical subsystems and the construction of the prototype of the first intelligent article of clothing with active thermal protection. Fig. 15 shows the results of the final integration of all the technical subsystems into the shoulder, chest and waistband thermoinsulating chamber and represents the first practical prototype design. It should be emphasized that there has been no article of clothing which changes its thickness so entirely new in concept and function in the field of clothing engineering.

5. Conclusions

The paper describes the idea, concept, patent protection and practical/technical constructional and design details of an intelligent article of clothing with active thermal protection.

The following phases of the project can be observed:

- The notion of the operating mode of the thermoinsulating chambers was developed, such that could be integrated into clothing with the aim of achieving theromoinsulation properties, adapting to the changes in the environment temperature and the microclimate temperature of the clothing. The idea of using different sets of thermoinsulating chambers, the combinations of which could offer different levels of thermal protection, was developed and realized. No construction of the type has been realized in the field of clothing technologies until now.
- The idea that the level of thermal protection should be activated automatically was developed and realized. A sensor-microcontroller-actuator system was designed and constructed for these purposes. Its task was to measure the conditions of the environment and the clothing microclimate, to interpret them and to adapt to the desirable temperature of the thermal comfort of the clothing microclimate. It was also supposed to make decisions on the actuator activation and to independently establish the necessary level of thermal protection, using the pre-

defined activation matrix in the process. Since the article of clothing is able to find necessary solutions for the meaningful response to changes in its environment independently, it by definition assumes attributes of intelligent behaviour. The idea resulted in a prototype construction of the first intelligent article of clothing with active thermal protection, and the prototype designed was the first technical design of this kind of garment in the history of clothing technologies.

- The work on the construction and investigation of the properties of the thermoinsulating chambers is also a novelty from the aspect of selecting the material for the chamber walls that can satisfy the conditions of elasticity in wear, activation and deactivation, and which at the same time has the necessary construction strength and the possibility of joining complex shapes that should ensure air impermeability. The tests offered optimum results when using ultrasonic welding of polymer materials, while the other joining procedures were not adequate for the purpose (gluing, heat conduction and heat convection joining). The results of measuring samples of the thermoinsulating chambers, as well as the testing methodology applied, are a novelty in themselves. Changes in the dimensions of the thermoinsulating chambers in the inflated state, relevant for garment construction and the optimum pressure of the activated chamber (50 mbar), were tested by measurements.
- Although some technical solutions of the integration of electronic, electrical and engineering components into clothing have already been patented and published, the micropneumatic elements were integrated into clothing for the first time and a complex integration of several synchronized technical subsystems was successfully accomplished. The subsystems were particularly developed for precisely specified functions and integrated into the garment (temperature and pressure measuring sensors, the microcontroller system, the actuator system and the system for rational consumption of integrated battery resources). In the scientific field of clothing technologies no integration of two or several technical subsystems into clothing has been realized until now. The prototype of the intelligent article of clothing with active thermal protection described here is distinguished by an exceptional complexity and the fact that it is the first of its kind.

The new intelligent article of clothing with active thermal protection described here will serve as a basis and stimulus for subsequent, exceptionally interesting scientific investigations in the field of clothing engineering, related to the development of intelligent clothing in the future, algorithms of intelligent behaviour of this kind of clothing, computer construction of special clothing which changes its shape and thickness during wearing, construction of thermoinsulating chambers, ergonomics of wearing garments of variable dimensions and thermodynamic properties.

For the work on the intelligent article of clothing with active thermal protection the team of scientists received the first prize for innovations in high technologies and the most innovative Croatian high-technology product (VIDI e-novation prize called Tesla's Golden eye in the category of individual innovators for 2007).

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