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FUZZY CONTROLLED SYSTEM FOR HYPOTHERMIC BRAIN THERAPY

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We propose a device for therapeutic hypothermia implemented with Peltier elements controlled by a microcontroller, operated from a guided user interface. The control is based on fuzzy logic and aims at keeping a low temperature in the specified brain regions. The design takes into account the uncertainties of the application and the nonlinear behavior of the cooling devices.

Key words: hypothermia, Peltier elements, microcontroller, fuzzy logic implementation, fuzzy rules.

1. INTRODUCTION

Hypothermia for therapeutic purposes is used for the cooling on some areas of patient's body. Therapeutic hypothermia is a procedure used to reduce the risk of ischemic tissue injury following a period of insufficient blood supply [1–3]. The insufficient supply with blood may be caused by heart failure or blockage of arteries when an embolism occurs, as it usually happens after stroke. Therapeutic hypothermia is also used in tumor treatment, where it prevents alopecia resulting from chemotherapy and decreases the psychological and social impact of chemotherapy on the patients.

Studies have shown that patients under risk for ischemic brain injury present better results using hypothermic methods of treatment [1, 2]. These studies were focused on researching ischemic accidents that, unlike usual strokes, reduces coagulation threshold. These researches shown that therapeutic hypothermia has a neuroprotective effect [1, 2]. Various studies showed as well that therapeutic hypothermia controls intracranial pressure (ICP) after an ischemic stroke and is a safe and feasible procedure [1–3]. Medical therapeutic hypothermia may be implemented using invasive techniques, where, for example, heat transportation is directed by a catheter inserted into the femoral vein, or through non-invasive methods, based on cold water or ice.

In cases related to strokes, to reduce the waiting time before the intervention, ambulances must be equipped with mobile devices for hypnotherapy therapeutics. However, such devices should operate as much as possible in a self-controlled manner, without a medical expert. We propose in this paper a portable system, based on Peltier cooling elements and fuzzy control. This is the first attempt in the literature to design Peltier-based, self-controlled devices for therapeutic hypothermia, taking into account the uncertainties related to the problem and the nonlinear behavior of Peltier elements. The only other paper on the subject is [4], but their device has not the facilities [5] of the device we present. While several applications of fuzzy logic were proposed and tested for medicine, for example [4, 6, 7], only a few are used today. We believe the proposed system is a suitable application for fuzzy system control, for motives explained in the paper.

2. METHOD

Various authors proposed the construction of devices for induced hypothermia for medical purposes, in order to control the cooling of specific areas and tissues on the head [1–4], of other parts of the body [8, 9]. The use of Peltier coolers for cooling various electronic devices is well known; see for example [10]. This type of device is also largely used, for example for food cooling, spacecraft temperature control systems, and in cooling high power semiconductor devices. Thermoelectric coolers (TECs) based on the Peltier effect are preferred in hypothermia because they have small thickness, low weight, lack of moving mechanisms, high precision, and safe operation. For primary experiments, we used four TECs and further consider to increase their number to 20. The size of Peltier elements is 40×40 mm. Two TECs are used on each half of the skull. For the future we plan to improve the precision and complexity of the temperature field and for this reason we will use smaller TECs. It is required to take into account the minimum acceptable temperature under TECs, not to degenerate, or completely freeze the skin tissue. For this, we calculate a minimum temperature and limit the maximum current through the Peltier.

In spite of their advantages, Peltier TECs have limitations. One of them is the fact that the temperature of the cooling element is strongly dependent on the ambient temperature. For this reason, it is necessary to develop a model of the cooling, to determine the dependence on ambient temperatures with good accuracy.

Manufacturers offer a variety of thermoelectric devices with multiple limit values ($\Delta T_{\max}, I_{\max}, V_{\max}$ and $Q_{\max}$), but common manufacturers unfortunately do not provide information about the physical parameters in catalogs (s, ρ and k – see below) of the devices. This makes the design difficult. Huang et al. [11] have developed a method for high precision measurement of the physical parameters of TECs, but the measuring requires a long time. The TECs have a nonlinear law [12–16], which needs a nonlinear controller. The equations (1) and (2) for a TEC are provided in many handbooks and papers, e.g. [12, 14–16]:

$$Q_c = 2N\left[sIT_c - I^2/2\rho/G - kG\Delta T\right], \tag{1}$$

$$V = 2N\left[I\rho/g + s\Delta T\right], Q_p = VI, Z = s^2/\rho k\,, \tag{2}$$

where Q_c is the transported heat flux, $\boldsymbol{N}$ is the number of pairs of thermoelectric elements, s is Seebeck coefficient [V/K], $\boldsymbol{I}$ is the current [A], T_c is the cold side (ambient) temperature [K], T_h is the hot side (that is, head) temperature [K], ρ is resistivity [Ω·cm], G is area/length of thermoelectric element (cm), k is thermal conductivity [W/cm·K], ΔT is $T_h - T_c$ [K], V is voltage [V], Q_p is the power input for TEC [W], $\boldsymbol{Z}$ is the figure of merit, $s^2/\rho k$ [K^{-1}]. Equation (1) shows that the extracted heat depends quadratically on the current through the TEC. The graph $Q_c = Q_c(I)$ has a maximum at a current value $I_{\max}$ that depends on the ambient temperature T_c and on the temperature of the body, T_h. The maximum is determined from $\mathrm{d}Q_c(I)/\mathrm{d}I = 0$ as $sT_c - I_{\max}\rho/G = 0$, thus $I_{\max} = sT_cG/\rho$.

A specific problem with hypothermia is that the heat conduction from the region to be cooled inside the body (including the case of the head) to the surface is limited, while there is a lowest allowed temperature at the surface of the body (skin), $T_{skin-\min}$, due to potential necrosis of the skin. Therefore, equations (1) and (2) should be completed at least with the model of heat conduction of the body, according to

$$T_{in} - T_{skin} = T_{in} - T_h = Q_{source}/R_{th-head}\,, \tag{3}$$

where T_{in} is the internal temperature of the region to be cooled, $T_{skin} = T_h$ (the skin is the hot surface for the TEC), Q_{source} is the heat source in the region of the head to be cooled (under the TCEs), and $R_{th-head}$ is the thermal resistance from the source to the skin, in the respective region. The cooled head region and the cooling system have different thermal capacities and resistances; they have different thermal time constants, thus making the control more difficult. However, one can assume that the time constant of the head section of the thermal circuit is much higher than that of the TEC system, when the last one is well designed.

3. SYSTEM DESCRIPTION

3.1. Electronic system

The block diagram of the hypothermal therapy device (Fig. 1) includes the cooling modules, the control and measurement module, and the interface on the PC. In this implementation, the cooling module consists of four Peltier elements and the corresponding power supply drivers. MOS-FET transistors

(IRF3808) are typically used for control of the Peltier elements. The duty-cycle (D_c) of a PWM (pulse width modulation) signal is modified for the control. The control and measurement module consist of a µC ATMEGA 16 and four digital sensors (DS18B20) for temperature monitoring. They measure the temperature with a resolution of 12 bits, with an error of 0.1°C.

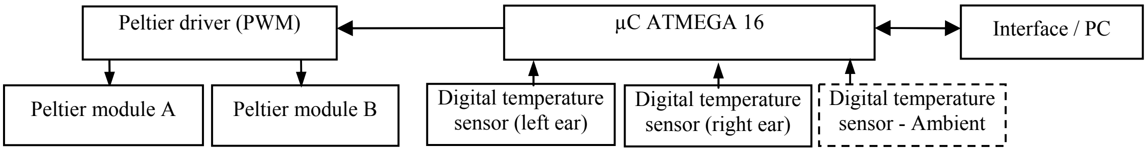

Fig. 1 – Electronic system – block diagram. The ambient temperature sensor is not used in the current version of the system.

The temperature sensors are connected by the 1-wire protocol on the µC data-bus. The Atmega16 microcontroller was chosen because it is a cheap microcontroller; it runs the algorithms, controls the cooling elements and checks the temperature of the body region of interest. To drive the Peltier elements, we use a fuzzy control that modifies the duty cycle of the PWM signals. To generate four PWM signals, timer modules are used, working at 115.2 kHz frequency. An USART module is used to modify and control the necessary parameters and for visualization of the temperature. The sampling of the temperature data and the control can be performed at low frequencies (for example, one time per 1–10 seconds), because of the high thermal inertia of the system. The Peltier TECs can be driven continuously, with a stop condition when the target temperature is obtained, with a circuit as in [17]. The same circuit could be used to drive the TECs by impulse sequences, to extend the capabilities of pure PWM driving.

The therapeutic hypothermia apparatus is designed to operate autonomously. In case that there is a need to change the treatment program, changes can be made to the program from any computer with an USB port. The user interface displays the temperature of the monitored areas and allows setting the desired (target) temperature of the head (ears) [5]. We use a control similar to the one recommended in other applications of Peltier elements [18], but using fuzzy logic to take into account the numerous uncertainties in the process.

3.2. Fuzzy logic controller

Because the cooling is a complex non-linear and uncertain process, we use a control algorithm based on fuzzy logic. Fuzzy logic methods are closer to the "human approach" control and management and allow medical experts to provide knowledge in a manner well understood by them, see examples in [19, 20]. Fuzzy set and fuzzy logic, introduced by Lotfi Zadeh, allow us to describe the inexact concepts in our knowledge of the word, as well as offers opportunities in order to gain new information. The methods based on this theory allow to obtain information models, greatly extending the possibilities of using traditional computers in medicine, by "fuzzy modeling" [6, 19, 20].

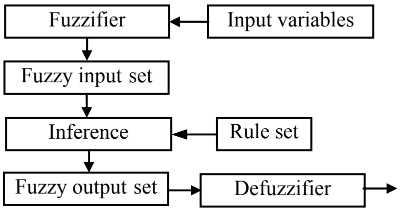

Fig. 2 – Fuzzy system principle.

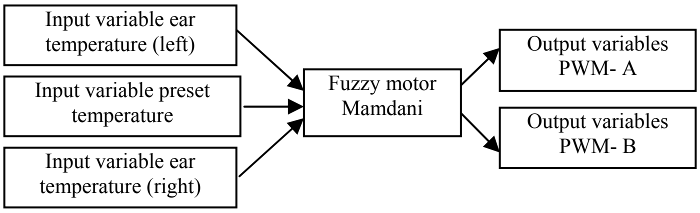

Fig. 3 – Principle of the fuzzy inference motor.

The main causes of uncertainties and randomness in the hypothermia treatment process, which encourages the use of the fuzzy logic control, are as follows:

– The heat production in the region of interest in the subject brain varies from subject to subject, even for the same subject between different treatment sessions. In addition, the heat dissipation varies at different temperatures of the brain; also, heat production may vary during the session depending on the state of the subject. In addition, the inside head temperature is determined as the ear temperature, which is an accepted, but imperfect method of measuring [9].

– The heat extraction process depends on the % RH of the air and on the incident IR radiation on the Peltier elements plus heat sinks, which is unknown or undefined in general (heat from direct sun light, from lamps etc.); moreover, air flow, and consequently heat dissipation are not well known. All these factors may play an important role in the cooling process efficiency.

– The constants of the Peltier elements are not precise (tolerances are in the range of 10% or more).

The principle of operations of a fuzzy logic system and the general structure of the system we used are shown in Figs. 2 and 3. For the control, the parameters of the Peltier TECs are taken into account in the design; the input values are the ambient temperature, the body temperature, and the target body (head) temperature preset by the physician - measured on the ear. We considered several control strategies. In the first one, the ambient temperature is not measured, and the control uses two inputs, namely the target temperature, T_t, set by the doctor and the ear temperature, T_e. This type of control has little flexibility and is essentially a simple proportional control, which is naïve. Essentially, this control produces the controlled parameter, duty cycle, D_c, as a function of T_t and $T_e, D_c = D_c(T_t, T_e) \approx D_c(T_e - T_t)$, almost the same as for a single input variable, $T_e - T_t$. A second strategy would be to use both the current value of the parameters T_t and $T_e, T_t[n]$ and $T_e[n]$, and their previous values, $T_t[n-1]$ and $T_e[n-1]$, to take into account, in this way, the speed of cooling. A more advanced control should take into account all the conditions in the problem, including the ambient temperature, T_a, as $D_c = D_c(T_t[n],\ T_e[n],\ T_t[n-1])$. This case can be simplified to two inputs in the controller, $T_t[n] - T_e[n],\ T_t[n-1] - T_e[n-1]$, with one control surface for every specified interval of ambient temperatures. In this case, the system needs two temperature measurements (for one ear; three measurements for two ears), as shown in Fig. 1. In the tests reported in the next sections, we use only three membership functions (m.f.s) for the inputs and the output. The reduced members of input m.f.s allows a simple description by the medical expert, while the large set of output member functions allies line central of the temperature. The control is symmetric, meaning that we need two controllers considering that the two ears may have different temperatures. The rule table is shown for a single ear, for one side of the median line in case of cooling system composed of symmetrically placed four TECs. Basically, the cooling system with rules in Table 1 is a proportional control system (high induces low temperature) of the duty cycle of the PWM.

Table 1

Set of rules to control Peltier elements, for the simplest control strategy (proportional)

Ear temp / Preset temperature	low	normal	high
low	small	normal	high
normal	small	normal	normal
high	small	small	small

In the final operation in the fuzzy control, the output fuzzy variables from the fuzzy inference are converted by defuzzification into quantitative values of each of the output variables (the four duty cycle values), using the formula [19, 21], $y = \int x\mu(x)\mathrm{d}x / \int \mu(x)\mathrm{d}x$. The integrals are over the entire domain of definition of the m.f.s. The defuzzification is known to produce some difficulties for some choices of the output m.f.s [21], but these problems can be easily avoided in design.

4. RESULTS

The desired temperature is set by the medical practitioner using the interface shown in Fig. 4. The same interface is used to visually monitor the temperature of the ear(s) of the patient during hypothermia. We simulated under Matlab the behavior of the control system for hypothermia. An example of output membership functions and of the control surface is presented in Figs. 5, 6 (simulation in Matlab). This is only one of the cases of the control, which is case-based. The acceptable temperature range is divided into sub-intervals of 5°C; for every sub-interval another definition for the output m.f.s is given, to maintain a good efficiency of the TECs, according to equations (1–3). This makes the controller adaptive interval-wise.

Central for obtaining good results is the smoothness of the control surface, which can be noticed in Fig. 6. Another essential feature is the limiting value of the current (due to the maximal duty cycle factor in the control output value); this feature depends on the external temperature and its limitation prevents the loss of efficiency of the TEC operation. The smoothness of the control surface is obtained by an appropriate choice of the membership functions, including the choice of their degrees of overlapping.

Fig. 4 – User's interface.

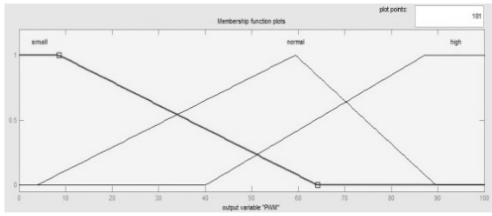

Fig. 5 – Output variable "PWM duty cycle", after manual adjustment.

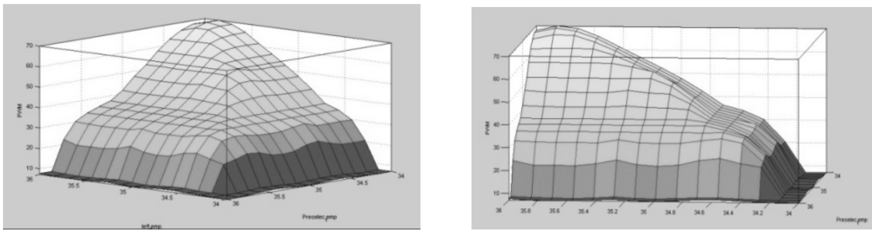

Fig. 6 – Input-output function of the fuzzy controller, after trimming the input and output membership functions.

The PWM output must be transformed into d.c. current, to prevent vibration production that may destroy the tissue or the TEC elements (see [18] "current ripple above 3% degrades the TEC's cooling efficiency.") In addition, the dynamics of the cooling is not good if not fast stabilizing; the output m.f., before defuzzification, which represents a fuzzy sequence, should be fast convergent to the zero membership function, see [22]. From another perspective, using temporal fuzzy sets [23] and the terminology in [24], the temporal fuzzy sets associated to the output m.f.s of the control block must have the attractor centered on the origin of the axes and occupying a small area. These problems remain to be investigated in the future. Improvements of the control can be made with more complex strategies for fine control using neuro-fuzzy [25] or adaptive fuzzy controls, [26]. In the future, it is conceivable that doctors give the desired law of variation of the head temperature and the controller follows that law.

5. DISCUSSION AND CONCLUSIONS

We proposed, designed and partly built and tested a preliminary version of an apparatus for hypothermic therapy used in medical purposes for directed cooling of specific tissues, using Peltier elements. Peltier cooling elements allow elaboration of a small mobile device that can be operated in emergency medical services, in this way reducing the risk of ischemic tissue trauma after heart failure or blockage of arteries.

The use of fuzzy logic control enables the construction of flexible algorithms. Also, fuzzy linguistic variables and simple expressions describing the membership functions are well understood by medical practitioners and improve their collaboration to the design of the system. There are however several problems with TEC based hypothermia and with fuzzy control. The main one is that the system has to be at least partly adaptive: Peltier elements work less well when the ambient temperature is higher than the body temperature, or when the ambient temperature is lower but close to the body temperature; therefore, an input to the controller must be the temperature difference between the two. Considering the inertia of TECs and the thermal inertia of the human body, which is varying from patient to patient, it is useful to use in the future inputs and rules to consider previous values of the temperature, in a predictive-type controller. Concluding, the proposed and partly tested hypothermia system has advantages over similar ones, including flexibility of the control, ease of being understood by medical personnel, and potential for adaptability.

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REFERENCES

1. HOLZER, M., *Mild hypothermia to improve the neurologic outcome after cardiac arrest*. New England Journal of Medicine. **346**, *8*, pp. 549–556, 2002.
2. MAYER, S. and SESSLER D. (Eds.), *Therapeutic Hypothermia*, M. Decker, New York, 2004.
3. POLDERMAN, K.H., *Application of therapeutic hypothermia in the ICU, 2,* Intensive Care Med., **30**, *5*, pp. 757–69, 2004.
4. AHISKA, A. H., YAVUZ, M., KAYMAZ & GÜLER, İ., *Control of a thermoelectric brain cooler by adaptive neuro-fuzzy inference system*, Instrumentation Science & Technology, **36,** *6*, pp. 636–655, 2008.
5. COJOCARU, V., MARDARI, V., NICA, I., *Device for hypothermic therapy,* 2nd Int. Conf. Nanotechnologies and Biomedical Engineering, Chişinău, Apr. 18–20, 2013.
6. TEODORESCU, H.N., KANDEL, A., HALL, L., *Report of research activities in fuzzy AI and medicine at USF CSE,* Artificial Intelligence in Medicine, **21**, *1–3*, pp. 177–183, Jan–Mar 2001.
7. TEODORESCU, H.-N., MLYNEK, D. et al., *Analysis of chaotic movements and fuzzy assessment of hands tremor in rehabilitation*, Knowledge-Based Intelligent Electronic Systems, 1998. Proceedings KES '98 IEEE, 1998 Second International Conference, **3**, pp. 340–345, 21–23 Apr. 1998, Adelaide, Australia.
8. MORIZANE, K. et al., *A novel thermoelectric cooling device using Peltier modules for inducing local hypothermia of the spinal cord*, Neuroscience Research, **72,** pp. 279–282, 2012.
9. DEMIREL, H., GÖKTAŞ, H., ERKAL, B., CIYLAN, B., *Prediction of the brain temperature from other body temperatures in hypothermia induced rats by using artificial neural networks*, Comp. in Biology and Med., **42**, *7*, pp. 772–777 July 2012.
10. NAJAFI, H., WOODBURY, K.A., *Optimization of a cooling system based on Peltier effect for photovoltaic cells,* Solar Energy **91**, pp. 152–160, May 2013.
11. HUANG, B., CHIN, C., and DUANG, C., *A design method of thermoelectric cooler*, International Journal of Refrigeration, **23**, *3*, pp. 208–218, 2000.
12. PÉREZ–APARICIO, J.L., PALMA, R., TAYLOR, R.L., *Finite element analysis and material sensitivity of Peltier thermoelectric cells coolers*, International Journal of Heat and Mass Transfer, **55,** *4*, pp. 1363–1374, Jan 2012.
13. MANNELLA, G., LA CARRUBBA, V., BRUCATO, V., *Peltier cells as temperature control elements: Experimental characterization and modeling*, Applied Thermal Engineering **63**, *1*, pp. 234–245, Feb 2014.
14. CHEN, L., MENG, F., SUN, F., *Effect of heat transfer on the performance of thermoelectric generator-driven thermoelectric refrigerator system*, Cryogenics, **52**, *1*, pp. 58–65, Jan 2012.
15. LUO, Z., *A simple method to estimate the physical characteristics of a thermoelectric cooler,* 2008; www.electronics-cooling.com/2008/08/a-simple-method-to-estimate-the-physical-characteristics-of-a-thermoelectric-cooler-from-vendor-datasheets/.
16. Wavelength Electronics, Inc., Technical Note TN-TC01 Rev C., *Optimizing Thermoelectric Temperature Control Systems*, Oct 2005; http://www.teamwavelength.com/downloads/notes/tn-tc01.pdf.
17. TEODORESCU, H.N., COJOCARU, V., *Three-transistor modulator-amplifier circuit works with swept-control frequencies*, Electronic Design (EDN), **55**, *8*, pp. 72-+, 2010.
18. Maxim Integrated Products, Inc., Tutorial 1757, *HFAN-08.2.1: PWM Temperature Controller for Thermoelectric Modules*, Feb 26, 2003; http://www.maximintegrated.com/en/app-notes/index.mvp/id/1757
19. LUUKKA, P., *PCA for fuzzy data and similarity classifier in building recognition system for post-operative patient data*, Expert Systems with Applications **36**, *2*, pp. 1222–1228, 2009.
20. PAPAGEORGIOU, E., DE ROO, J., HUSZKA, C., COLAERT, D., *Formalization of treatment guidelines using Fuzzy Cognitive Maps and semantic web tools,* Journal of Biomedical Informatics, **45**, *1*, pp. 45–60, Feb 2012.
21. TEODORESCU, H.N., *On the characteristic functions of fuzzy systems*, International Journal of Computers, Communications & Control, **8** *3*, pp. 469–476, Jun 2013.
22. TEODORESCU, H.N., *On fuzzy sequences, fixed points and periodicity in iterated fuzzy maps*, International Journal of Computers, Communications & Control, **6**, *4*, pp. 752–763, Dec 2011.
23. KOSANOVIC, B., CHAPARRO, L., SCLABASSI, R., *Signal analysis in fuzzy information space*, Fuzzy Sets and Systems, **77**, pp. 49–62, 1996.

24. RODRIGUEZ, W., TEODORESCU, H.N., GRIGORAS, F., KANDEL, A., BUNKE, H., *A fuzzy information space approach to speech signal non-linear analysis*, International Journal of Intelligent Systems, **15**, *4*, pp. 343–363, Apr 2000.
25. TEODORESCU, H.N., *Taylor and bi-local piecewise approximations with neuro-fuzzy systems,* Studies in Informatics and Control, **21,** *4***,** pp. 367–376, Dec 2012.
26. PRECUP, R.-E., DAVID, R.C., PETRIU, E., PREITL, S., RĂDAC, M.-B., *Experiments in fuzzy controller tuning based on an adaptive gravitational, search algorithm*, Proceedings of the Romanian Academy, Series A, **14**, *4*, pp. 360–367, 2013.

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