Intelligent Exoskeleton Structures for Military Applications

Ştefan A. DUMITRU[1], Danut A. BUCUR[1], Mircea BOŞCOIANU [2] and Luige VLADAREANU[1]

[1]Robotics and Mechatronics Department
Institute of Solid Mechanics of the Romanian Academy
15 C-tin Mille, Sector 1, Bucharest, Bucharest, ROMANIA
luigiv2007@yahoo.com.sg, dumitru_sa@yahoo.com, dan.bucur@ymail.com, http://www.imsar.ro

[2]Department of Military Sciences and Management
"Henry Coandă" Air Force Academy
160 Mihai Viteazul, Braşov, ROMANIA
mircea_boscoianu@yahoo.co.uk   http://www.afahc.ro/

Abstract: - To improve human locomotory performance (strength, endurance, speed) in military applications, an exoskeleton structure (ES), that runs parallel to the legs, transferring payload to the ground, is studied. Exoskeleton control can be done by different methods having as input the EMG signal coming from human muscle. While using, the energy consumption of the ES is high and to ensure the autonomy, the system needed power is harvested from human body using high-tech micro devices.

Key-Words: exoskeleton structure (ES), military applications, artificial intelligence, energy harvesting

1 Introduction

An example of enhancement human locomotor performance (strength, endurance, speed) is expressed by the exoskeleton structure (ES) than runs parallel to the legs, transferring payload to the ground [4, 5]. For better efficiency of this system, passive hip and angle springs are used to store and release energy. In metabolic experiments are suggested the use of an orthotic exoskeleton to augment human load carrying capabilities with robust reduction of the cost of locomotion.

The "Spring Walker Concept" support a moderate running pace and is based on kinematic linkage whose joints incorporated springs.

The "hybrid assistive leg" HAL3 employs harmonic drive motors at the heap, knee and ankle joints [1]. With a control strategy focused on the estimation of the human's joint torques and the use of feed forward algorithm to command torques to the motors. The "Berkley Lower Extremity Exoskeleton" BLEEX used linear hydraulic actuators to power the hip, knee and ankle in the sagittal plain [2]. The control strategy is based on the use of intelligent control implemented using only measurements from the exoskeleton. A similar concept named SARCOS used rotary hydraulic actuators located at the hip and knee and the control algorithm is based on 20 sensors on each leg processed on dedicated computer. The disadvantage of SARCOS is represented by the noise of the internal combustion engine which limits military applications. Recent trends in exoskeleton development are focused on powered exoskeletons for military applications (estimated to require 500W of steady state power at running speeds, capable to achieve by using future battery technology). A powered exoskeleton is more complex than the conventional metabolic reduction for load carrying and the interest is to simply this architecture. A solution in this direction is considered to be the micro-mechanical energy harvesters [3]. They are the product of micro / nano technologies advancement. They are very small devices (1 cm3 in volume) used to extract energy from the human body. It is well known that human body converts in energy the most part of the gathered calories.

In this paper we present an overview about the energy harvesters and the control methods than may apply to the exoskeleton. The paper is structured in four sections. The first one is an introduction part where the state of the art is treated. In section 2 is formulated the control problem and we propose in section 4 two possible solutions for it. In section 3 few types of energy harvesters are presented. Section 5 concludes this paper and it comprehends the future works that the authors want to develop next.

2 Problem Formulation

The exoskeleton robot applies torques to the subject's joints to resist the movement. Figure 1 shows the block diagram of the control method for the exoschelet. The signal of target muscles is recorded through surface EMG electrodes. This signal represents the reference input for the control sistem. In this paper we present two control systems whose input is the EMG signal and whose outputs are the commands to drive the motors. The control algorithms could be applied both on elementary body parts like upper leg, forearm, and on a group of body parts that move independent to each other, like hands, legs or trunk.

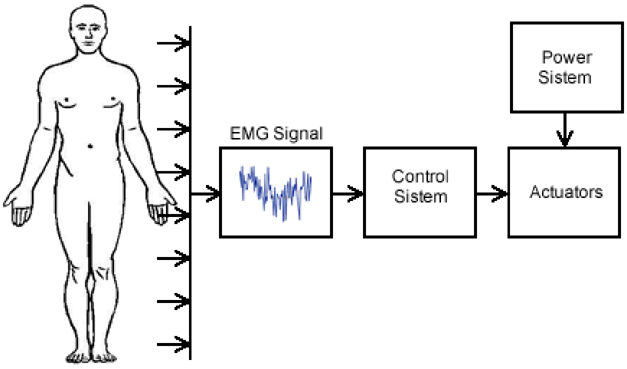

Fig. 1. Block diagram for exosckeleton control sistem.

Using the exoskeleton needs a lot of energy. To increase autonomy a constant energy flow must be provided. Equipping the exoskeleton with advanced energy harvesting technology provides energy flow.

3 Micro-devices for energy harvesting

Implanted biomedical devices represent possible drug dosing approaches to the patients who suffer from severe diseases such as diabetes, colon cancer and heart disease. Being electronic devices, the power supply is a consistent problem. The most appropriate way to solve this problem consists in the extraction of energy from the human body. This operation is also known as energy harvesting or energy scavenging. Microelectromechanical systems (MEMS) are the materialization of this idea. They are light weight, recharge-free and tiny size (1cm^3 in volume) devices. Among these characteristics, these energy harvesting devices have to preserve the anti-infection property of the implanted biomedical devices; they have to be biocompatible with the patient's body and also, they must be designed in accordingly to the harvested energy parameters such as motion's amplitude and frequency.

A person of an average body size stores chemical energy up to 380 MJ [6]. The stored energy is partially consumed by the daily activity as shown in Table 1 [6].

Table 1: Human energy consumption

Activities	Kilocal/h	Watts
Sprinting	1400	1630
Long distance run	900	1048
Mountain climbing	600	698
Swimming	500	582
Hiking, 6.5 km/h	350	407
Standing at ease	110	128
Sitting	100	116
Sleeping	70	81

The energy provided by human body can be classified as follows: physical and chemical energy as shown in Fig. 1. So far, only few chemical energy harvesting MEMS are known [7] (e.g. a microbial fuel cell able to convert glucose into electricity by electrochemical reaction [7]).

Due to the fact that batteries are hard to replace or externally recharged the major problem of the implanted biomedical devices is lifespan of power supply sources (e.g. lithium iodine batteries) [8].

Due to the progress in the field of micro/ nano technologies, MEMS-based energy harvester seems to be the best solution that fits the problem of power source for the implanted biomedical devices.

There are four categories of MEMS: Kinetic energy harvester, micro-biofuel energy harvester, airflow energy harvester, thermal energy harvester. These devices are presented in the following.

3.1. Kinetic energy harvester

Motion-induced kinetic energy is one of most useful and popular energy sources in human body and this could represent most important power supply for MEMS. This kind of energy is produced by arm motion or walk.

MEMS have the ability to convert efficiently into electricity low speed and high torque mechanical power. In terms of mechanical dynamics a major problem is caused by joint power intermittency and time-varying

Based on the operation mode, the kinetic energy harvesters can be classified as follows.

1. *Electrostatic energy harvester* – the mechanical energy can be converted into electrical energy based on the gap variation of a pre-charged capacitor pair

which will induce an electrical field. An external load is added in order to complete the energy conversion circuit (fig. 2)[3]

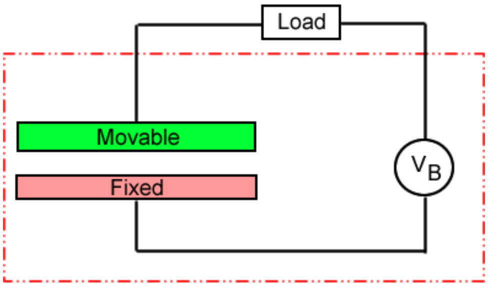

Fig. 2. Electrostatic capacitor

The capacitance for the variable capacitor is given by

$$C(t) = \frac{\varepsilon A}{\left(g_0 - x(t)\right)} \tag{1}$$

where ε is the dielectric constant, A the plate area, g_0 the initial gap between the two plates and $x(t)$ the displacement of the movable electrode.

The electrical output power of the MSHE is equal to the product of the current flowing through the external load and the corresponding voltage drop.

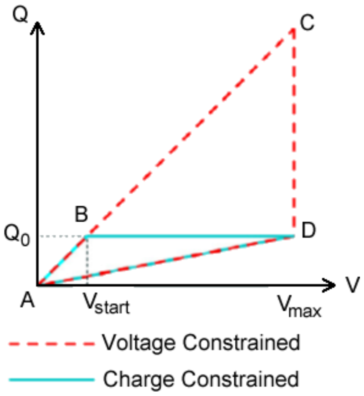

Fig. 3. Conversion cycles for micro-electrostatic energy harvester [15].

These types of harvesting devices have two operation principles (fig. 3)[15]: constant charge (the voltage is increased and the capacitance is decreased) and constant voltage (the charge is decreased as the capacitance is decreased).

2. Piezoelectric energy harvester - This type of energy harvesters works on the piezoelectric effect. The conversion from mechanical to electrical energy is made using piezoelectric materials such as ZnO. The electrical field is induced as the piezoelectric material is physically deformed, as shown in Fig. 4.

The equations for a piezoelectric material are presented below:

$$\delta = \left(\frac{\sigma}{E_Y}\right) + dE_e \tag{2}$$

$$D = \varepsilon E_e + d\sigma \tag{3}$$

where δ and σ are mechanical strain and stress. E_Y is Young's Modulus. d is the piezoelectric strain coefficient. E_e is the electric field, D the charge density and e the dielectric constant of the piezoelectric material.

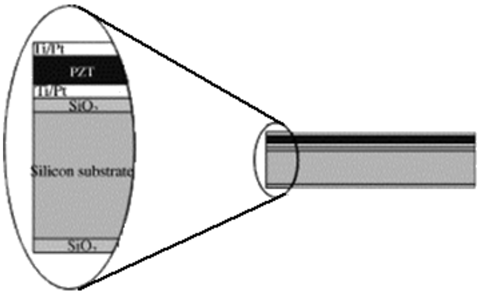

Fig. 4. Micro piezoelectric energy harvester

3. Magnetic induction energy harvester – the operation mode of this type of device is based on Faraday's law: the induced electromotive force (EMF) in any closed circuit is equal to the rate of change of the magnetic flux in time. The mathematical expression is given below:

$$|\varepsilon| = \left|\frac{d\Phi_B}{dt}\right| \tag{4}$$

where ε is the magnitude of the EMF and Φ_B is the magnetic flux through the circuit (in webers). The variation in magnetic flux, Φ_B, through an electrical circuit induces an electric field. A magnetic induction energy harvester is made of a rotor and an induction coil, as shown in Fig. 5.

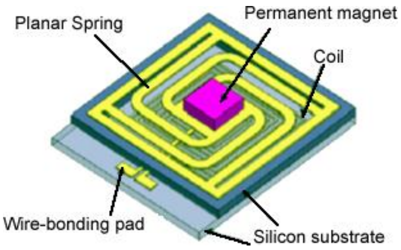

Fig. 5. Micro electromagnetic energy harvester [3]

The voltage is generated across the coil exerting an external vertical vibration making the magnet oscillate about Z-axis (this will change the magnetic flux at the coil).

3.2 Micro-biofuel energy harvester

Micro-biofuel energy harvester is a device that generates electricity from endogenous substances through electrochemical reactions. Glucose is the most pertinent fuel source for this kind of harvest systems [9]. A micro-biofuel energy harvester is shown in Fig. 6. The electric current density of a microfluidic biofuel cell is decreased if the length of the electrode is increased in the direction of convective flow. From the point of view of power output and biocompatibility, the biofuel harvesting devices could be superior to other energy harvesting devices, but they present a short longevity an insufficient amenability to steam sterilization.

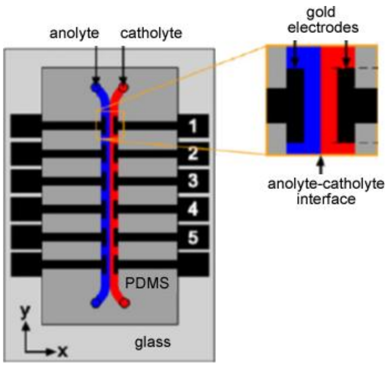

Fig. 6. Microfluidic biofuel energy harvester [10]

3.3 Airflow energy harvester

Air flow from the respiration could be a potentially energy source that can be converted into electric power using a micro-turbine. The average respiratory rate for a healthy adult at rest mode is about 12 breaths per minute (0.2 Hz) [11] and the breathed air volume is about 500-600cm3 (fig. 7).

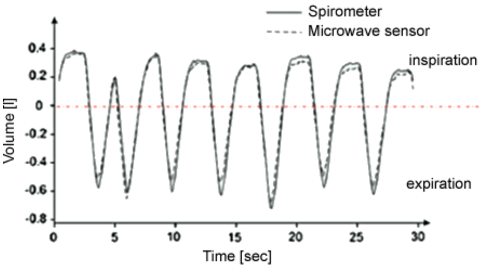

Fig. 7. Average inspiration volume flow of healthy adult at rest mode [3]

3.4 Thermal energy harvester

Thermal gradient is another energy source for the implanted biomedical devices. The normal core body temperature under various room temperature is about 36.0 -37.0 C and is shown in figure 8.

Micro thermal energy harvester (MTEH) converts the temperature gradient in the environment into electrical energy by Seebeck (thermoelectric) effect [12]. This type of energy harvester is consists in two materials connected in series and a thermo generator which produces electrical power proportional to the difference of temperature between these materials. In order to complete the electric circuit, an external load is added (fig 9).

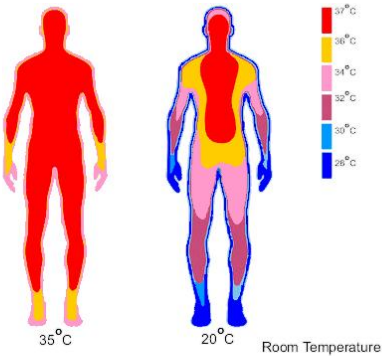

Fig. 8. Human skin temperature at different room temperature

The induced voltage by the thermal energy harvester is given by:

$$V_{out} = (\alpha_n - \alpha_p)\Delta T \tag{5}$$

where α_n and α_p are known as Seebeck coefficients of p-type and n-type semiconductors respectively.

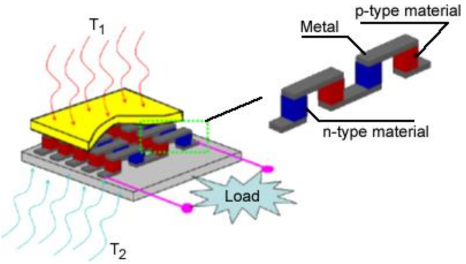

Fig. 9. Micro-thermoelectric energy harvester

The optimal thermal resistance obtained through this device is:

$$R_{MTEH} = \frac{(R_{body} + R_{si})R_{et}}{2(R_{body} + R_{si}) + R_{et}} \tag{5}$$

where $R_{body}$is the thermal resistance of human body at which the MTEH is located. R_{si} is the thermal resistance of a heat sink, i.e., the thermal resistance due to convection and radiation on the outer side of MTEH, and R_{et} the thermal resistance of MTEH.

The energy harvested depends on the ratio N, between the size and thickness of METH device so that the thinner MTEH, the less power can be scavenged.

$$N = \frac{R_{et}}{(R_{body} + R_{si})} \tag{6}$$

4 Control System

4.1. Reactive neural control

A first method of control is the reactive neural control described in Figure 10 [13]. This is a control method that analyses with a neural network data obtained from sensors. Neural network has to filter and process the signal in order to give a direct command to actuators.
In our case, reactive control system will constantly analyze signals from EMG sensors which are mounted on the skin surface of the human subject.

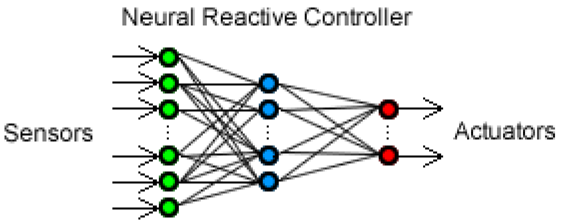

Fig. 10. Operating principle of Reactive Neural Control

The first option considered is to control a larger group of links and related joints. This approach involves dividing the exoskeleton in many parts that normally move independently of each other. The entire exoskeleton is divided into five main parts, independent of each other, ie two hands, two legs and trunk.

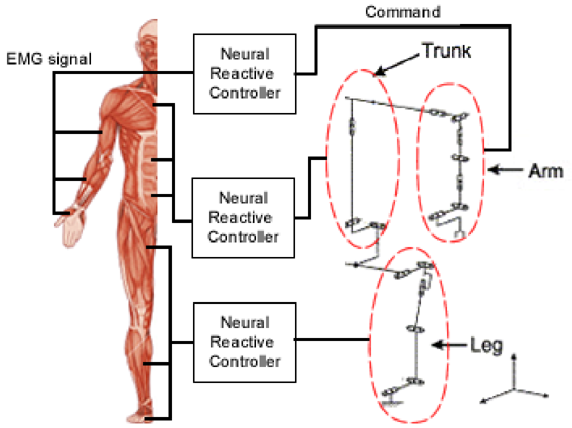

Fig 11. Body parts that work independently from each other and the way that exoskeleton is actuated.

Figure 11 shows the block diagram of this approach. Note that there are 5 reactive neural controls driving the motors related to considered body part.

The second approach assumes a controller for each link. This approach offers modularity characteristic of control system. The control algorithms could be applied both on elementary body parts like upper leg, forearm, or on a group of body parts that move independent to each other, like hands, legs or trunk The control, shown in figure 12, is performed similar to first approach.

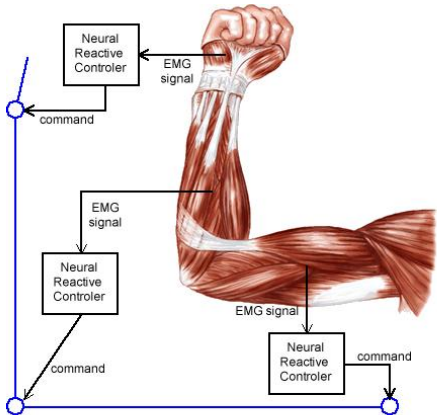

Fig. 12. Exoskeleton drive through modular control

4.2. Neuro fuzzy controller

Another possible control method is the neuro-fuzzy inference system. Because is a hybrid control, the system is transparent due to fuzzy systems and adaptable due to neural networks. Takagi-Sugeno-Kang (TSK) method [14] involves generating fuzzy "if-then" rules which establish a relationship between inputs and outputs:

$$\begin{aligned} &R_i: if\ x_{i1}\ is\ A_{i1}, then \\ &\qquad y = c_{i0} + c_{i1}x_1 + \cdots + c_{in}x_n \end{aligned} \quad (7)$$

where N_R is the number of rules, $x = [x_1, x_2, \dots, x_n]$ is the input vector, y_i is the output of the i-th rule, A_{ij} are the antecedent fuzzy sets that are characterized by membership functions $\mu_{A_{ij}}(x_j)$, and c_{ij} are real-valued weight parameters

The output is:

$$\begin{aligned} y &= \frac{\sum_{i=1}^{N_R} \tau_i y_i}{\sum_{i=1}^{N_R} \tau_i} \\ &= \frac{\sum_{i=1}^{N_R} \tau_i (c_{i0} + c_{i1}x_1 + \cdots + c_{in}x_n)}{\sum_{i=1}^{N_R} \tau_i} \end{aligned} \quad (8)$$

where τ_i is the firing strength of the rule R_i , which is defined as

$$\tau_i = A_{i1}(x_1) \times A_{i2}(x_2) \times \dots \times A_{in}(x_n) \quad (9)$$

where "×" operator represents fuzzy "and".

This system offers the possibility of high precision control depending on several parameters. Also, analyzing posture and accelerations that occur during movement, a neuro-fuzzy controlled exoskeleton can improve the stability the person using it. Application of the method is similar to that described above but the output of the control system depends on many parameters and the accuracy is high.

5 Conclusion

This paper presents an overview of the actual concepts/ architectures of exoskeleton systems. The interest to enhance the performance of human locomotory (strength, endurance, speed) is essential in military application (the well known concept of future soldier) and it opens a new branch of dedicated research. The basic principles and applications are explained together with the way to solve the dedicated problem and the technological solutions. Based on a global energy analysis are also analyzed the human load carrying capabilities with focus on the solutions/ configurations/ architectures capable to cut the cost of locomotion and to enhance the real autonomy of these systems in a robust functioning. A detailed analysis is dedicated to the comparative analysis of different types of control architectures. In this case are suggested the artificial intelligence ingredients to use in order to obtain better performance of exoskeleton systems.

The procedure of aligning the exoskeleton to the human in order to allow the normal human motion is the most important task and the focus will be on how to interface the rigid exoskeleton to the human in a manner that it enables a normal fluid movement.

Future work should be focused on details regarding the interface of the exoskeleton to the human, the development of new control algorithms (for example: to respond to variable dumping knee's), the integration of mono-directional elastic energy storage which replaces the multidirectional elastic carbon composite foot-ankle, additional power at the hips in order to enhance the performance via the optimization of the power needed in the system.

References:

[1] Kawamoto, H., Sankai, Y. Power assist system HAL-3 for gait disorder person, *Computers helping people with special needs, 8th International* Conference ICCHP 2002, Springer (2002), p.196-203

[2] Kazerooni, H., Racine, J.-L., Huang, L., and Steger, R. On the Control of the Berkeley Lower Extremity Exoskeleton (BLEEX). *IEEE International Conf. on Robotics and Automation*, Barcelona, Spain, 2005.

[3] Chung-Yang Sue, Nan-Chyuan Tsai, Human powered MEMS-based energy harvest devices, *Applied Energy 93 (2012)*, pp. 390–403, doi:10.1016/j.apenergy.2011.12.037

[4] P. Malcolm, P. Fiers, V. Segers, I. Van Caekenberghe, M. Lenoir, D. De Clercq, Experimental study on the role of the ankle push off in the walk-to-run transition by means of a powered ankle-foot-exoskeleton, *Gait & Posture 30 (2009), pp.* 322–327, doi:10.1016/j.gaitpost.2009.06.00

[5] Jun Ueda, Ding Ming, Vijaya Krishnamoorthy, Minoru Shinohara, and Tsukasa Ogasawara, Individual Muscle Control using an Exoskeleton Robot for Muscle Function Testing, *Neural Systems and Rehabilitation Engineering, IEEE Transactions on*, Volume: 18, Issue: 4 pp. 339 – 350

[6] Starner T, Paradiso JA. Human generated power for mobile electronics. *CRC Press; 2004*. p. 1–35.

[7] Chiao M, Lam KB, Lin L. Micromachined microbial fuel cells. *Proc of the IEEE micro electro mechanical systems*; 2003. p. 383–6.

[8] Gensler H, Sheybani R, Li PY, Lo R, Zhu S, Yong KT, et al. Implantable MEMS drug delivery device for cancer radiation reduction. *IEEE 23rd international conference on micro electro mechanical systems*; 2010. p. 23–6.

[9] Wang P, Tanaka K, Sugiyama S, Dai X, Zhao X, Liu J. A micro electromagnetic low level vibration energy harvester based on MEMS technology. *Microsyst Technol 2009*;pp. 941–51.

[10] Sari I, Balkan T, Kulah H. An electromagnetic micro power generator for lowfrequency environmental vibrations based on the frequency upconversion technique. *J MEMS 2010*; pp. 14–27.

[11] Tortora GJ, Anagnostakos NP. Principles of anatomy and physiology. *6th ed. New York: Harper-Collins*; 1990. p. 20–59.

[12] Boniche I, Masilamani S, Durscher RJ, Morgan BC, Arnold DP. Design of a miniaturized thermoelectric generator using micromachined silicon substrates. *J Electr Mater 200*9; pp. 293–302.

[13] Poramate Manoonpong, Hubert Roth, Reactive neural control for autonomous robots: From simple wheeled robots to complex walking machines, *The Fifth International Conference on Neural Networks and Artificial Intelligence,* Minsk May 2008.

[14] T. Takagi, M. Sugeno, Fuzzy identification of systems and its application to modeling and control, *IEEE Trans. SMC,* pp. 116-132, 1985

[15] Mizuno M, Chetwynd DG. Investigation of a resonance microgenerator. *J Micromech Microeng 2003*, pp. 209–16.