Multiobjective Optimization-based Design of Wearable Electrocardiogram Monitoring Systems

F. J. Martinez-Tabares[1] J. A. Jaramillo-Garzón[1,2] G. Castellanos-Dominguez[1]

Abstract— **Nowadays, the use of Wearable User Interfaces has been extensively growing in medical monitoring applications. However, production and manufacture of prototypes without automation tools may lead to non viable results since it is often common to find an optimization problem where several variables are in conflict with each other. Thus, it is necessary to design a strategy for balancing the variables and constraints, systematizing the design in order to reduce the risks that are present when it is exclusively guided by the intuition of the developer. This paper proposes a framework for designing wearable ECG monitoring systems using multiobjective optimization. The main contributions of this work are the model to automate the design process, including a mathematical expression relating the principal variables that make up the criteria of functionality and wearability. We also introduce a novel yardstick for deciding the location of electrodes, based on reducing interference from ECG by maximizing the electrode-skin contact.**

I. INTRODUCTION

Cardiac diseases are the leading cause of death worldwide. In fact, the number of patients requiring continuous monitoring incessantly grows, and by the 2025 year, this group may reach as much as 1.2 billion [1], [2]. Electrocardiogram (ECG) is the most common tool used to diagnose heart failures. A feasible option for cardiac remote supervision is the implementation of Wearable Monitoring Systems (WMS) or sensorized clothing devices that are emerging as an interesting and reasonable solution for situations requiring computation and mobile sensors. Thus, wearable monitoring systems (WMS) in healthcare applications are gaining tremendous attention motivated by continued miniaturization and cost reduction of micro/nano electronic components [3], [4]. However, attempts to produce and directly manufacture prototypes based only on the designer's intuition mostly may lead to non viable results causing cost overruns in construction tests.

Generally speaking, design and construction of WMS imply new standards aimed at industrial hygiene, risk management, infection control, safety from radiation, costs, and physical security, among others. All those issues are increasingly influenced by new methodologies of interdisciplinary work that combines medicine, engineering, physics and management among other disciplines in order to choose a set of correct settings following formal design procedures. Particularly, the increasing trend of human-centered devices has led to the creation of the ISO `13407` standard (human-centered design processes for interactive systems) [5] and ISO `9241-210` (Ergonomics of human-system interaction) [6]. Besides, there are several platforms facilitating design of customized products: WUI-Toolkit [7], Abstract UI [8], SUPPLE [9], Huddle [10], and Context-Framework [11], etc.

Nonetheless, design of human-centered devices mostly appraises multiobjective formulations where objectives may have different nature and priorities, according to system and designer's preferences. To fulfill health care requirements of cardiac monitoring, the determination of the proper system variables holding bounds and constraints to achieve system objectives is needed. One of the simplest approaches to explore design spaces is the searching algorithm based on integer linear equations [12]. Yet, because of heterogeneity of system formulations, multiobjective optimization approaches have been also developed in human-centered devices design [13]. However, to analyse multiobjective-based systems, suitable solutions are based on a ranking of the input objectives, which in practice is unknown and nearly impossible to estimate [14].

This paper develops a WMS system within a human-centered design framework for ambulatory medical monitoring systems. The WMS is assumed to be used in places strongly different from any traditional workspace [15]. To get the best design option, we use a multi-objective optimization approach based on genetic algorithms and using information about state-of-the-art platforms. Carried out optimization approach is devoted the concrete designing of an ergonomic clothing article holding textile electrodes and having anti-fluid protection. As a result, we improve the wearability and functionality of the WMS prototypes by introducing a novel criteria to place electrodes that consists in reducing interference from ECG by maximizing the contact quality of the EEG sensor.

II. METHODS

A. Optimization design space

The design space is where the problem statement is made by the definition of variables, constraints, and objective functions. So, to achieve the system objectives of the WMS manufacturing process under design, we will assume three groups of the target variables, namely: functionality, wearability, and energy. Selection of those target variables in WMS

[1]Universidad Nacional de Colombia, Manizales, Signal Processing and Recognition Group, Colombia [2]Instituto Tecnológico Metropolitano, Medellín, Grupo de Automtica, Electrnica y Ciencias Computacionales, Colombia {fjmartinezt,cgcastellanosd}@unal.edu.co

*This work is supported by ARTICA and COLCIENCIAS grants: 523 and Generacion Bicentenario.

design implies a trade-off among comfort, communication cost, energy consumption, and processing performance [16].

To optimize the above set of nonlinear objective functions for a provided multi-objective criteria, the use of evolutionary algorithms have been proposed in [13]. To this end, a set of solutions known as the *Pareto front* is to be obtained during optimization of the set of multiple targets. Thus, the conventional multi-objective optimization problem consists on finding a vector of decision variables $\boldsymbol{x}^* = [x_1, \ldots, n_n]$ that satisfies m inequality constraints and p equality constraints, while optimizing a vector function $\boldsymbol{f}(x) = [f_1(x), f_2(x), \ldots, f_k(x)]$ whose elements are k-th objective functions $f_i(x)$, $\forall\ i = 1, \ldots, k$.

At the beginning, the optimization process starts with the specification of the objective functions as well as the set-up of the design constraints. From these data, a group of initial solutions lying in the search space is defined. Then, a set of the introduced rules is iteratively applied to those solutions for making them evolve until each one of them can fulfil the Pareto front. Thus, each reached solution within the Pareto front represents a possible trade-off among the design parameters. Based on the Pareto front solutions, the designer selects an optimal architecture according to the scenario, where the wearable system is to be deployed.

B. Proposed multi-objective optimization-based design model

Here, we propose the following salient variables influencing the functionality (g_1) and wearability (g_2) of the WMS, and their estimated growth rates are listed in Table I.

Variable		Cited references	Criteria g_1	Criteria g_2
x_1	Skin contact quality, body fit and body placement	[16], [17]	$\propto x_1^2$	$\propto -x_1$
x_2	Size	[13], [17], [16]	$\propto x_2$	$\propto -x_2$
x_3	Weight	[13], [16], [17], [18]	$\propto x_3$	$\propto x_3$
x_4	Fluid repellency	[19]	$\propto x_4$	$\propto x_4$
x_5	Magnetic protection and radiation concerns	[16], [18]	$\propto x_5$	$\propto -x_5$

TABLE I
CRITICAL VARIABLES OF THE SYSTEM

*1) **Functionality,** g_1:* Besides the maximum latency and the repetition frequency referenced in [13], we hypothesize that the most critical requirements for cardiac monitoring systems are: accuracy, precision, specificity, sensitivity, false negative rate. All these parameters are determined largely by the contact between the electrode and the skin, i.e. the distance between electrode and skin guarantees the stable and high quality biopotential measurement. To this matter, authors in [20] propose an expression for the maximum value of normalized cross correlation as a function of the distance between two electrodes placed on opposite sides of the muscle belly. Therefore, we conclude that the amplitude of the measured surface potentials of a muscle decays exponentially as long as the electrode distance increases. In this manner, signal quality is strongly influenced by the compression or adhesion of the garment; the contact quality (x_1) is assigned as an exponential function, namely, a quadratic function.

We also suggest to relate functionality with hygiene items that are determined according to the level of antibacterial protection, through an anti-fluids coating whose efficiency is measured by the angle of inclination between water drops and the textile material. The proposed coating does not affect the conductivity of the electrodes. This information feeds the generic model to search for such areas to place wearable electrodes that are the best in terms of reducing the power line variations caused by loosening of the electrodes. The contribution of x_2 to x_5 is assumed to have a linear growth, as follows:

$$g_1 = (x_1^2 + x_2 + x_3 + x_4 + x_5)/14 \qquad (1)$$

The values are assigned in terms of percentage so that the sum must be divided by 14 to normalize the result.

*2) **Wearability,** g_2:* Wearability is defined as the interaction between the human body and a wearable object. Yet, we extend the dynamic wearability definition as to include the human body in movement. According to [13], the system wearability factor g_2 is defined by the sum of the module wearability factors F_{mod} of all modules m.

The module wearability factor $F^m_{mod} \sum_r \vec{\boldsymbol{W}}^p \cdot \vec{\boldsymbol{w}}_r$ is the sum of the abstract wearability factors of all allocated resources for a specific module m at a given location p. A wearability vector $\vec{\boldsymbol{w}}_r = (w_1, w_2, ..., w_n)$ is assigned to each resource. Resources are divided into devices and channels. Each element of the vector $\vec{\boldsymbol{w}}_r$ corresponds to one variable influencing the wearability. $\vec{\boldsymbol{W}}^p$ is the pth column of the wearability weight matrix $\boldsymbol{W} = (\boldsymbol{W}^1 \ldots \boldsymbol{W}^p \ldots \boldsymbol{W}^n)$ and contains the relative importance of the factors at column $\vec{\boldsymbol{W}}^p$.

$$g_2 = \sum_m \sum_r \begin{bmatrix} \vec{\boldsymbol{w}}_1^p \\ \vdots \\ \vec{\boldsymbol{w}}_n^p \end{bmatrix} \cdot (w_1, w_2, ..., w_n) \qquad (2)$$

The wearability concept depends on a variety of ergonomic criteria, among others: weight , size, correspondence between form and location in the body, aspects related to radiation, heat and aesthetics; all of the generating the need of a non-invasive implementation. So the restriction is given as follows:

$$g_2 = (-x_1 - x_2 + x_3 + x_4 - x_5 + 300)/5 \qquad (3)$$

III. EXPERIMENTS AND RESULTS

The Multiobjective Optimization-based Design of Cardiac Monitoring Systems is implemented that include two system objectives: wearability and functionality, as seen in Fig. 1, the multi-objective genetic algorithm (GAMO) is used to explore the design space [16]. As result, The Pareto front is computed and one of its solutions is chosen that should better represent a given design architecture. Finally, a cloth is manufactured under the obtained specifications of architecture as a case of study.

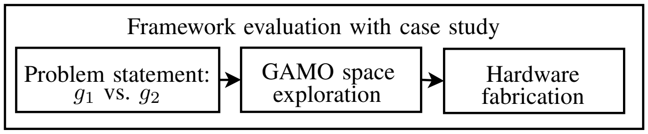


Fig. 1. Design and test procedure of the Multiobjective Optimization-based Design of Cardiac Monitoring Systems

A. Problem statement

Here, the aim is to build a three ECG-leads garment that should be optimized in terms of functionality, wearability, hygiene, and real-time operation. Therefore, we search for a vector of architecture models $\boldsymbol{x}^* = [x_1, \ldots, x_n]$ that optimizes the vector function $\boldsymbol{y} = (y_1, y_2)$ as follows:

$$\boldsymbol{y} = [f_1(x_1, x_2, x_3, x_4, x_5), f_2(x_1, x_2, x_3, x_4, x_5)] \quad (4)$$

$$y_i = f_i(x_1, x_2, x_3, x_4, x_5) \quad (5)$$

Since multi-objective optimization problems are usually formulated in terms of minimization, we propose the inverse equations describing functionality ($\boldsymbol{g}_1$) and wearability ($\boldsymbol{g}_2$). Specifically, the Eq. 5 is stated as a vector $\boldsymbol{y}$ comprising two objective functions: $f_i(x), \forall i = 1, 2$, where the first one is the lack of functionality, y_1, give as:

$$y_1 = f_1(x_1, x_2, x_3, x_4, x_5) = 100\% - g_1 \quad (6)$$

while the second one is lack of wearability, termed obstrusivity, y_2,:

$$y_2 = f_2(x_1, x_2, x_3, x_4, x_5) = 100\% - g_2 \quad (7)$$

B. GAMO space exploration and Pareto front

The iterative search process provides a set of trade-offs represented by the Pareto front, as shown in Fig. 2, each point corresponds to a specific configuration. The designer considered that solution located at the point $y_1 = 44.98\%$ and $y_2 = 25.66\%$ reaches an adequate trade-off between functionality and wearability, at the same time, ensuring a lightweight garment and moderately pressing the body. As a result, the values obtained for the variables are: $x_1 = 69.45\%$, $x_2 = 33.03\%$, $x_3 = 99.95\%$, and $x_4 = 99.89\%$.

After selecting the needed architecture model from the Pareto front, construction and validation of the hardware are conducted. Table II shows relationships between the objective functions, elements to build, and specific performance tests.

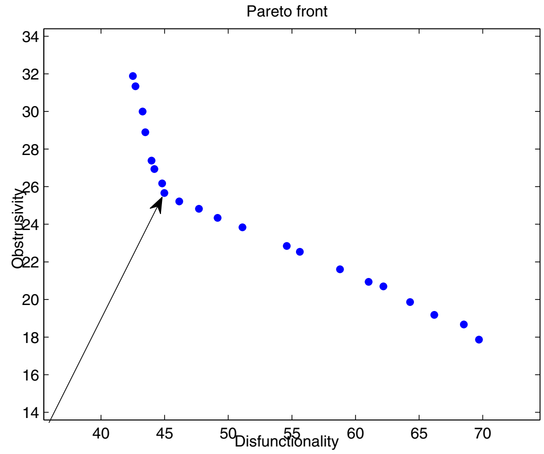


Fig. 2. Computed Pareto front

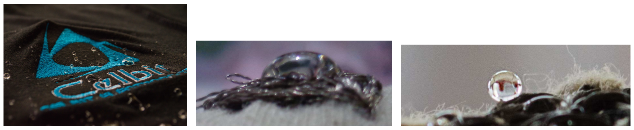
Criteria	Optimization objective		Performance test
	General	Specific	
g_1 / g_2	To acquire a high quality ECG signal with a comfortable, lightweight system	Building dry, long-term electrodes and verifying superhydrophobic properties of the SiO_2 film	Electrical resistance, distortion metrics, contact angle, physicochemical & morphological analysis

TABLE II
OPTIMIZATION OBJECTIVES AND PERFORMANCE TEST

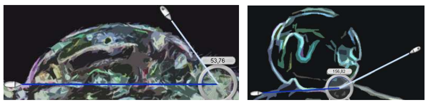
During implementation, the `Medtex P130` conductive textile is used to construct the electrodes over a t-shirt made of viscose-spandex in order to maximize signal quality and ergonomics. Besides, with the aim of minimizing biological contamination, coatings of silver and nanoparticles of silicon dioxide (SiO_2) are applied over the garment. Silver can effectively repel bacterial agents, while the super-hydrophobic coating minimizes the adherence of microorganisms and contaminants. The silver-based coating is obtained from the same fabric used to make the electrodes (Fig. 3(a)), which has a three-layer of Tin, Copper and 99% Silver on a substrate of Nylon fiber. The preparation of the electrodes is tested by forming bags made with conductive material, on which is applied Nano-SiO_2 using the technique of High Volume Low - Pressure (HVLP) in spray, adjusted for FDA 21 CFR 172.48 standard, prepared by the sol-gel method.

To confirm the superhydrophobicity, the angle between the solid-liquid interface is estimated, and the roughness and separation of the particles as well as the composition thereof is determined. The angle is measured by taking a high-resolution photograph of a drop deposited on the fabric. A digital filter is applied to the image to highlight the edges of the drop, this facilitates that a software goniometer determines the angle between the drop and the material.

(a) Textile (b) The Garment (c) Wet fabric



(d) Hydrophobic (e) Wetting Drop (f) Water droplet



(g) Angle in wetting drop (h) Angle hydrophobic

Fig. 3. Fig. 3(a): Fabric used to manufacture the electrodes, Fig. 3(b): Picture of the built garment. The contact angle between the fabric and the water drops is measured with a digital goniometer: (Figs. 3(c), 3(e), 3(g)). Before the treatment, the fabric is completely impregnated with water, in general terms, all angles are inferior to 90°. After the treatment, the angle is larger than 156° (Figs. 3(d), 3(f), 3(h))

IV. Discussion and concluding remarks

Wearable Monitoring Systems are becoming increasingly common, however, their design requires finding the right balance between the competing variables involved in the process. For this reason, a platform that simplifies that goal is used.

In this direction, a platform based on multi-objective optimization with genetic algorithms, achieves an appropriate compromise between the conflicting variables. Particularly, the performance of the platform heavily depends on the elements that integrate the generic model. The range of the generic model, is a crucial element to improve the desired design, because the biggest database returns many more results in the Pareto front. The authors propose an inverse relation between wearability and functionality in the specific case of the compression exerted by the garment to fix the textile ECG electrodes to the chest. Thus, the stronger compression, the better signal quality, but the user comfort is decreased. Likewise, it is important to mention regarding the identification of the best places to connect ECG electrodes, we have concluded that any point of the chest or limbs is suitable to measure this variable, being the only one condition necessary to ensure an adequate signal quality, to keep a stable contact.

To improve the functionality, it has also proposed the use of fluid protection with superhydrophobic nanoparticles that do not affect the conductivity of the material. Flexible, conductive textile electrodes with a comfortable sensation were added to the architecture model, so that the functionality and wearability levels are improved.

As future work, the authors plan to process information transmitted to the Internet in real time, including stages of selection and extraction of features as well as classification. It is also of interest to include more sensors to increase the amount of useful information about the patient. Besides, it is necessary to make a similar analysis, including the energy consumption of the system.

References

[1] M. M. Baig, H. Gholamhosseini, M. J. Connolly, A comprehensive survey of wearable and wireless ecg monitoring systems for older adults., Med. Biol. Engineering and Computing 51 (5) (2013) 485–495.

[2] I. for Health Metrics, Evaluation, The Global Burden of Disease: Generating Evidence, Guiding Policy European Union and European Free Trade Association Regional Edition, Seattle, WA: IHME, 2013.

[3] A. Harbouche, M. Erradi, A. Kobbane, A flexible wireless body sensor network system for health monitoring, in: Enabling Technologies: Infrastructure for Collaborative Enterprises (WETICE), 2013 IEEE 22nd International Workshop on, 2013, pp. 44–49.

[4] C. Bellos, A. Papadopoulos, R. Rosso, D. Fotiadis, Clinical validation of the chronious wearable system in patients with chronic disease, in: Engineering in Medicine and Biology Society (EMBC), 2013 35th Annual International Conference of the IEEE, 2013, pp. 7084–7087.

[5] ISO 13407:1999, Human-centred design processes for interactive systems, Tech. rep., International Standards Organization.

[6] I. O. for Standardization, Iso 9241-210:2010 ergonomics of human-system interaction – part 210: Human-centred design for interactive systems, Directly by the International Organization for Standardization.

[7] H. Witt, T. Nicolai, H. Kenn, The wui-toolkit: A model-driven ui development framework for wearable user interfaces, in: Distributed Computing Systems Workshops, 2007. ICDCSW '07. 27th International Conference on, 2007, pp. 43–43. doi:10.1109/ICDCSW.2007.80.

[8] C. Ahlrichs, M. Lawo, H. Iben, An abstract user interface framework for mobile and wearable devices., IJACI 3 (3) (2011) 28–35.

[9] K. Gajos, D. S. Weld, SUPPLE: Automatically Generating User Interfaces, in: Proceedings of the 9th International Conference on Intelligent User Interfaces, ACM, 2004, pp. 93–100.

[10] J. Nichols, O. Rothrock, D. H. Chau, B. A. Myers, Huddle: automatically generating interfaces for systems of multiple connected appliances, in: In UIST 06, ACM, 2006, pp. 279–288.

[11] A. K. Dey, G. D. Abowd, D. Salber, A conceptual framework and a toolkit for supporting the rapid prototyping of context-aware applications (2001).

[12] G. D. Micheli, Synthesis and Optimization of Digital Circuits, 1st Edition, McGraw-Hill Higher Education, 1994.

[13] U. Anliker, J. Beutel, M. Dyer, R. Enzler, P. Lukowicz, L. Thiele, G. Trster, A systematic approach to the design of distributed wearable systems., IEEE Trans. Computers 53 (8) (2004) 1017–1033.

[14] K. Lewis, F. Mistree, The other side of multidisciplinary design optimization: Accomodating a multiobjective, uncertain and non-deterministic world, Engineering Optimization 31 (2) (1998) 161–189.

[15] V. Carlsson, T. Klug, T. Ziegert, A. Zinnen, Wearable computers in clinical ward rounds, in: Applied Wearable Computing (IFAWC), 2006 3rd International Forum on, 2006, pp. 1–9.

[16] U. Anliker, H. Junker, P. Lukowicz, G. Trster, Design methodology for context-aware wearable sensor systems, in: H.-W. Gellersen, R. Want, A. Schmidt (Eds.), Pervasive Computing, Vol. 3468 of Lecture Notes in Computer Science, Springer Berlin Heidelberg, 2005, pp. 220–236.

[17] T. Starner, The challenges of wearable computing: Part 1, IEEE Micro 21 (4) (2001) 44–52.

[18] S. Park, S. Jayaraman, Enhancing the quality of life through wearable technology, Engineering in Medicine and Biology Magazine, IEEE 22 (3) (2003) 41–48.

[19] F. Martinez-Tabares, E. Delgado-Trejos, G. Castellanos-Dominguez, Wearable and superhydrophobic hardware for ambulatory biopotential acquisition, in: Engineering in Medicine and Biology Society (EMBC), 2013 35th Annual International Conference of the IEEE, 2013, pp. 1847–1850.

[20] L. Lindstrom, R. Magnusson, Interpretation of myoelectric power spectra: A model and its applications, Proceedings of the IEEE 65 (5) (1977) 653–662.