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A fuzzy method for the usability evaluation of nuclear medical equipment

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ABSTRACT

To avoid errors when handling nuclear medical equipment, it is important to develop products with a high degree of usability. This can be achieved by performing usability evaluations in the product development process to detect and mitigate potential usability problems. Usability evaluation focuses on how well users can learn and use a product to achieve their goals. To gather information about usability, practitioners use a variety of methods that gather feedback from users about an existing interface or plans related to a new interface. A wide range of usability evaluation methods have been proposed, but few methods focus on developing an objective and practical evaluation method for usability. Moreover, the usability evaluations are based on human judgments and most methods cannot fully solve the subjectivity of these evaluations. In order to remedy this deficiency, the purpose of this work is to adopt a Fuzzy Set Theory (FST) approach to establish a method for the usability evaluation of nuclear medical equipment based on usability heuristics for user interface design and international standards for ergonomics of human-system interaction. To exemplify the method we performed a usability evaluating of the Digital Spectrometer ESP 13004 by testing it with representative users. The results showed that the method is a proactive tool to provide a basis for checking usability of medical device interfaces.

Keywords: usability, fuzz logic, medical equipment.

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1. INTRODUCTION

Technology plays an important role in modern medical centers, making healthcare increasingly complex, relying on complex technical equipment. This technical complexity is particularly noticeable in nuclear medicine.

Human error has many causes such as performance shaping factors, organizational factors and user interface design. Poorly designed human-machine interfaces of nuclear medical equipment can increase the risks for human error. Although some manufacturers of nuclear medical equipment have already integrated human factors principles in their products, there is still a need to steer the development of nuclear medical technology toward more user-centered approaches. User-friendliness and ergonomics have become important quality characteristics for nuclear medical equipment [1].

The user interface is formed by presentations of information, data, controls and commands in computer screens. If all nuclear medical equipment had been designed with good user interfaces, incidents and accidents could be reduced as could the time required to learn how to use the equipment.

The usability evaluation of interfaces has as objective to prove that the functions and tasks placed for the users can be executed with safety. User interfaces must have high usability in order to create prerequisites for safe operation, installation, maintenance of nuclear medical equipment and increase the efficiency of the interaction operator system. Usability can be defined as the capacity of the system to allow users to carry out their tasks safely, effectively, efficiently and enjoyably [2][3].

To gather information about usability, practitioners use a variety of methods that gather feedback from users about an existing interface or plans related to a new interface. A wide range of usability evaluation methods have been proposed [2][4][5][6], but few methods focus on developing an objective and practical evaluation method for usability. Moreover, the usability evaluations are based on human judgments and most methods cannot fully solve the subjectivity of these evaluations. In order to remedy this deficiency, the purpose of this work is to adopt a Fuzzy Set Theory (FST) approach to establish a method for the usability evaluation of nuclear medical equipment based on usability heuristics for user interface design and international standards for ergonomics of human-system interaction. The FST provides an appropriate logical-mathematical framework to deal with uncertainty and imprecision of reasoning processes and situations. We describe the use of the proposed method in the Digital Spectrometer ESP 13004 by usability testing it with representative users.

1.1 USABILITY EVALUATION METHODS

Usability is a quality attribute that assesses how easy user interfaces are to use. The word "usability" also refers to methods for improving ease-of-use during the design process. According to the ISO 9241 standard [7], usability is defined as the product's attribute specifying the ease of use. It is described by the measure of effectiveness (can the goal of user be fully achieved), efficiency (what is the cost of achieving the goal), and satisfaction (which emotions, reactions are triggered in the user interaction with the device).

In the field of nuclear medical equipment, issues of usability have come to the fore, with the ultimate acceptance or rejection of systems such as records of patient radiation doses depending to a large extent on their degree of usability. Numerous studies have confirmed that the low usability of medical device interfaces has a significant impact on the growth of the used errors and it is a threat to patients [1].

Usability evaluation (UE) consists of methodologies for measuring the usability aspects of a system's user interface (UI) and identifying specific problems [5][8]. There are a variety of usability evaluation methods [2][4][5][6]. Certain methods use data from users, while others rely on usability experts. There are usability evaluation methods for all stages of design and development, from product definition to final design modifications. When choosing a method, consider cost, time constraints and appropriateness. The usability methods can be further classified into the following categories: cognitive modeling methods, inquiry methods, prototyping methods, testing methods and inspection methods.

Cognitive modeling involves creating a computational model to estimate how long it takes people to perform a given task. Inquiry methods involve collecting qualitative data from users. Although the data collected is subjective, it provides valuable information on what the user wants. Prototyping methods are performed to obtain rapid feedback on the usability of prototypes. Instead of creating the complete final system, the designer may test different sections of the system, thus making several small models of each component of the system. Testing methods involve testing of subjects for the most quantitative data. Usually recorded on video, they provide task completion time and allow for observation of attitude. Inspection methods involve observation of users by an experimenter, or the testing and evaluation of a program by an expert reviewer. They provide more quantitative data as tasks. The inspection method most commonly used is the heuristic evaluation.

Heuristic evaluation is a usability method for finding and assessing usability problems in a user interface design as part of an iterative design process. This method was developed to aid in the design of computer user-interface design. It relies on expert reviewers to discover usability problems and then categorize and rate them by a set of principles (heuristics) [5]. Heuristic evaluation is widely used based on its cost-effectiveness. On the other hand, heuristic evaluation is a subjective and unstructured method. Heuristic evaluation is based on people's perceptions, and it does not calculate the consistency among evaluators.

1.2 BASICS OF FUZZY LOGIC

Fuzzy logic provides an appropriate logical-mathematical framework to handle problems with such characteristics [9], since: (1) it deals with uncertainty and imprecision of reasoning processes and situations; (2) it allows the modeling of the heuristic knowledge that cannot be described by traditional mathematical equations and (3) it allows the computation of linguistic information.

Several studies show important reasons to use Fuzzy Set Theory (FST) [10][11][12]: reduction of human error, creation of expert knowledge and interpretation of large amount of vague data.

Fuzzy set theory (FST) is an extension of classical set theory where elements have degrees of membership. Let X be the universe of discourse and x a generic element of X, a fuzzy subset $\tilde{A}$, defined in X, is one set of the dual pairs (Eq. 1):

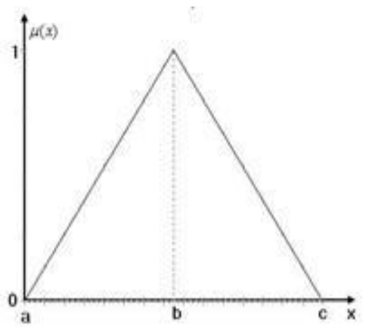
$$\tilde{A} = \{(x, \mu_{\tilde{A}}(x)) \mid x \in X\} \quad (1)$$

where $\mu_{\tilde{A}}(x)$ is the membership function or membership grade x in A. The membership function associates to each element x of X, a real number $\mu_{\tilde{A}}(x)$, in the interval [0, 1].
An α-cut or α-level set of a fuzzy set $\tilde{A} \subseteq X$ is an ordinary set $\tilde{A}_\alpha \subseteq X$, such that (Eq. 2):

$$\tilde{A}_\alpha = \{\mu_{\tilde{A}}(x) \geq \alpha, \forall x \in X\} \tag{2}$$

A fuzzy number is a special fuzzy subset of real numbers. Its membership function is a continuous mapping from R (real line) to a closed interval [0, 1]. Among the various shapes of fuzzy number, the triangular fuzzy number is the most popular one. A triangular fuzzy number $\tilde{A}$ can be denoted by *(a, b, c)* (Fig. 1) and its membership function is described in Eq. 3.

Figure 1: *Triangular fuzzy number*



$$\mu_{\tilde{A}}(x) = \begin{cases} \frac{x-a}{b-a} & ,if \quad a \leq x \leq b \\ \frac{c-x}{c-b} & ,if \quad b \leq x \leq c \\ 0, & otherwise \end{cases} \tag{3}$$

An important concept in fuzzy set theory is the concept of linguistic variables. A linguistic variable is a variable whose values are words or sentences in natural language, which can be represented as fuzzy sets.

2. MATERIALS AND METHODS

The fuzzy method for usability evaluation of nuclear medical equipment was structured according to the following steps:

(1) Selection of ergonomic criteria.

(2) Determination of an ideal usability pattern.

(3) Evaluation of the actual usability level compared with the pattern.

2.1 ERGONOMIC CRITERIA

The set of ergonomic criteria used in this work consists of a list of 14 elementary criteria based on Nielsen's heuristics [5] and studies on usability engineering [6][7][13]. The Nielsen's criteria are called "heuristics" because they are more in the nature of rules of thumb than specific usability guidelines. The operationalization of an ergonomic criterion is called “metric”. A metric denotes how the criterion is measured, whereas a criterion denotes something that one wishes to measure with the use of one or more metrics. The ergonomic criteria and the metrics are described in table 1.

Table 1: Ergonomic criteria and metrics.

Ergonomic criteria	Metrics
1. Action-effect consistency	Interfaces should contain measurement units that are compatible with the measured or input variables.
2. Consistency and standards	Users should not have to wonder whether different words, situations, or actions mean the same thing.
3. Aesthetic design	The interfaces should present visual distinction of areas and fields that have different functions.
4. Visibility of system status	The system should always keep users informed about what is going on, through appropriate feedback within reasonable time.
5. Colors	The colors used in the interface should allow a suitable contrast when reading functions, display and information.
6. Reading ability	Texts and messages should contain font size, spacing, and positioning appropriate for good on-screen reading.
7. Facilitation	Formatting of the numerical data should facilitate the reading, without the incidence of errors.
8. Minimum actions	Interfaces should contain a fast and simple way for navigation, minimizing the number of steps and the time for the selection of an action.
9. Information density	Interfaces should not contain information which is irrelevant or rarely needed to perform an action.
10. User control and freedom	Interfaces should give the user the freedom to browse and perform actions. Users often choose system functions by mistake and will need a clearly marked "emergency exit" to leave the unwanted state without having to go through an extended dialogue.

11.Help users recognize and diagnose errors	Error messages should be expressed in plain language (no codes), and precisely indicate the problem.
12. Protection against errors	The interfaces should present adequate separation between selectable and specific areas in order to minimize accidental actions.
13. Homogeneity and coherence	The characteristics of the interfaces (formats, data input areas) should be maintained consistent from one interface to another.
14. Meaning of the codes	Titles of the interfaces should be distinct from each other, with identification of the icons using appropriate technical terms employed in the task.

2.2 IDEAL USABILITY PATTERN

The second step of this fuzzy framework is to obtain from experts on evaluation of user interfaces and nuclear medical systems the degree of importance of each ergonomic criterion, so that a specific interface of nuclear medical equipment can be considered good and easy to use. This means that the degree of importance assigned to each criterion by the expert should show how the interface can achieve the maximum (ideal) usability level. Thus, this does not imply evaluation of the interface but the ideal usability that should be obtained. This phase has the following steps:

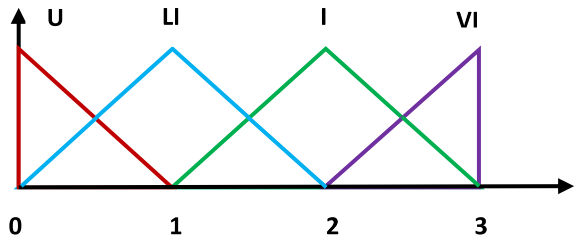
Calculation of experts' relative importance. The relative importance of the expert was calculated on the basis of experts' attributes (experience, knowledge of usability). We used a questionnaire (Q) to identify the profile. Each questionnaire contains information of a single expert. The relative importance (RI) of expert E_i (i = 1, 2, 3,…, n) is a subset $\mu_i(k) \in [0,1]$ defined by Eq. 4. Referring to Eq. 4, *tQi*, is the total score of expert *i*.

$$RI_i = \frac{tQ_i}{\sum_{i=1}^{n} tQ_i} \tag{4}$$

Choice of linguistic terms and membership functions. Each criterion can be seen as a linguistic variable, related to a linguistic terms set associated with membership functions. These linguistic terms are represented by triangular fuzzy numbers to represent the importance degree of each criterion (Fig. 2). It is suggested that the experts employ the linguistic terms, U (Unimportant), LI

(Little Important), I (Important) and VI (Very Important) to evaluate the importance of each indicator.

Figure 2: *Membership functions*



Aggregation of the fuzzy opinions. The similarity aggregation method proposed by Hsu and Chen [14] is used to combine the experts' opinions which are represented by triangular fuzzy numbers. The agreement degree (AD) between expert Ei and expert Ej is determined by the proportion of intersection area to total area of the membership functions. The agreement degree (AD) is defined by Eq. 5.

$$AD = \frac{\int_x \left(\min\left\{\mu_{\tilde{N}i}(x), \mu_{\tilde{N}j}(x)\right\}\right) dx}{\int_x \left(\max\left\{\mu_{\tilde{N}i}(x), \mu_{\tilde{N}j}(x)\right\}\right) dx} \tag{5}$$

If two experts have the same estimates, then, AD =1. In this case, the two experts' estimates are consistent, and then the agreement degree between them is one. If two experts have completely different estimates, the agreement degree is zero. If the initial estimates of some experts have no intersection, then we use the Delphi method to adjust the opinion of the experts and to get the common intersection at a fixed α-cut [14]. The higher the percentage of overlap, the higher the agreement degree. After all the agreement degrees between the experts are calculated, we can construct an agreement matrix (AM), which give us insight into the agreement between the experts.

$$AM = \begin{bmatrix} 1 & AD_{12} & \cdots & AD_{1j} & \cdots & AD_{1n} \\ \vdots & \vdots & & \vdots & \vdots & \\ AD_{i1} & AD_{i2} & \cdots & AD_{ij} & \cdots & AD_{in} \\ \vdots & \vdots & & \vdots & \vdots & \\ AD_{n1} & AD_{n2} & \cdots & AD_{nj} & \cdots & 1 \end{bmatrix} \tag{6}$$

The relative agreement (RA) of expert E_i (i = 1, 2, 3, …, n) is given by Eq. 7.

$$RA_i = \sqrt{\frac{1}{n-1} \cdot \sum_{j=1}^{n} (AD_{ij})^2} \tag{7}$$

Then we calculate the relative agreement degree (RAD) of expert E_i (i = 1, 2, 3, …, n) by Eq. 8 and the consensus coefficient (CC) of expert E_i (i = 1, 2, 3, …, n) by Eq. 9.

$$RAD_i = \frac{RA_i}{\sum_{i=1}^{n} RA_i} \tag{8}$$

$$CC_i = \frac{RAD_i \cdot RI_i}{\sum_{i=1}^{n} (RAD_i \cdot RI_i)} \tag{9}$$

Let Ñ be a fuzzy number for combining expert's opinions. Ñ is the fuzzy value of each leading indicator which is also triangular fuzzy number. By definition of the consensus coefficient (CC) of expert E_i (i = 1, 2, 3, …, n), $\tilde{N}$ can be defined by Eq. 9. Referring to Eq. 10, $\tilde{n}_i$, is the triangular fuzzy number relating to the linguistic terms, U (Unimportant), LI (Little Important), I (Important) and VI (Very Important).

$$\tilde{N} = \sum_{i=1}^{n} (CC_i \cdot \tilde{n}_i) \tag{10}$$

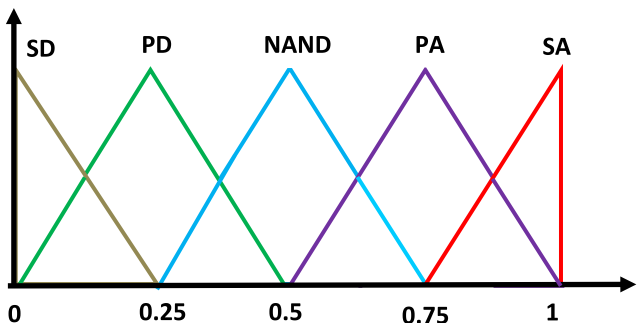
Ideal usability pattern. The ideal usability pattern as a reference for the usability evaluation of nuclear medical equipment is established by calculating the normalized importance degree (NID) of each ergonomic criterion that makes up each property relevant to design good user interfaces. The normalized importance degree (NID) of each ergonomic criterion is given by deffuzification of its triangular fuzzy number $\tilde{N}$ (a_i, b_i, c_i), where b_i represents the importance degree. Then, NID can be defined by Eq. 11.

$$NID_i = \frac{NID_i}{\text{the largest numerical value of bi}} \tag{11}$$

2.3 USABILITY EVALUATION BASED ON IDEAL USABILITY PATTERN

This third phase of the fuzzy method will be to obtain the actual level of usability as perceived by each user of the interfaces and compared it to the ideal usability pattern. In this step, the linguistic values will be used to assess the compliance degrees of the ergonomic criteria to a specific interface of nuclear medical equipment given by users. It is suggested that the users employ the linguistic terms, SD (Strongly Disagree), PD (Partially Disagree), NAND (Neither Agree Nor Disagree), PA (Partially Agree), SA (Strongly Agree) (Fig. 3).

Figure 3: *Membership functions for usability evaluation***.**



Using the center of area defuzzification method [15] will be calculated the compliance degree (CD) with the usability pattern by Eq. 12. In Eq. 12, *cd* is the compliance degree of the ergonomic criterion in the nuclear medical equipment.

$$CD = \frac{\sum_{i=1}^{k} NID_i . cd_i}{\sum_{i=1}^{k} NID_i} \quad (12)$$

3. RESULTS AND DISCUSSION

The usability evaluation of the Digital Spectrometer ESP 13004 was performed. This equipment was developed by the Nuclear Instrumentation Department of Nuclear Engineering Institute (IEN).

The Digital Spectrometer ESP 13004 is a nuclear pulse counting digital system, of easy operation and low power consumption, capable to assist mainly the activities related to nuclear medicine. The equipment is intended for measuring of ionizing radiations in diagnosis "in - vivo" and radiotherapy "in-vitro". The Digital Spectrometer was projected to be operated through one personal computer with specific software that offers multiple interfaces. The figure 4 shows one of the interfaces, the calibration interface. The ideal usability pattern was obtained based on the opinion of twelve experts in nuclear medical equipment. The usability evaluation of the Digital Spectrometer ESP 13004 was performed by ten representative users. The ideal usability pattern and the compliance degrees were computed and showed in table 2.

Figure 4: *Calibration interface of the Digital Spectrometer ESP 13004.*

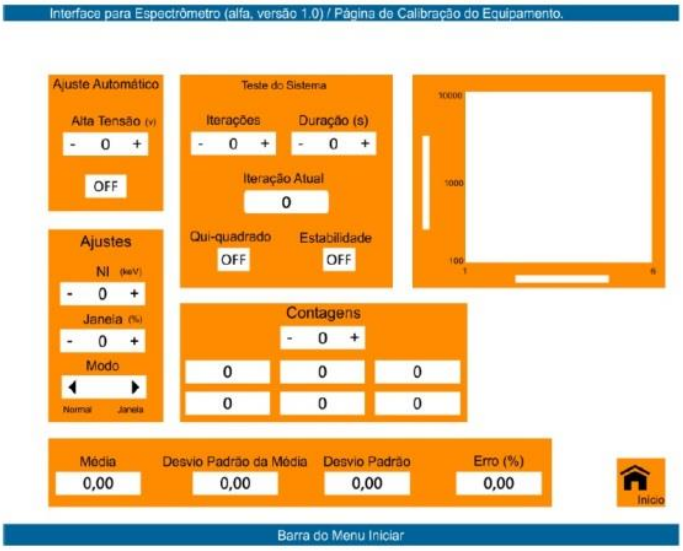


Table 2: Ideal usability pattern and compliance degrees.

Ergonomic criteria	Ideal usability pattern	Compliance degree
1. Action-effect consistency	0.791	0.91
2. Consistency and standards	0.900	0.91
3. Aesthetic design	0.899	0.94
4. Visibility of system status	0.995	0.38
5. Colors	0.768	0.97

6. Reading ability	0.891	0.94
7. Facilitation	0.827	0.84
8. Minimum actions	0.807	0.94
9. Information density	0.948	1.00
10. User control and freedom	1.000	0.47
11.Help users recognize and diagnose errors	0.753	0.25
12. Protection against errors	0.832	0.91
13. Homogeneity and coherence	0.946	0.97
14. Meaning of the codes	0.773	0.97

The evaluation method based on the metrics of the ergonomic criteria presented a compliance degree of the 0.81 with the ideal usability pattern. This result showed that the usability of the Digital Spectrometer ESP 13004 is satisfactory. However, this system presented problems related to three ergonomic criteria: “Visibility of system status”, “User control and freedom” and “Help users recognize and diagnose errors”. We consider satisfactory a compliance degree greater than 0.75, because this value already represents a strongly agreement with the ideal usability pattern (see Fig. 4). This represents a α-cut at 0.75 of the fuzzy set “ergonomic criteria”.

4. CONCLUSION

In this paper we described a method for usability evaluation of nuclear medical equipment. We proposed a method that uses ergonomic criteria and properties of Fuzzy Sets Theory. We developed a usability pattern using a similarity aggregation method to aggregate fuzzy individual opinions, considering the difference of importance of each expert. A pilot study in the Digital Spectrometer ESP 13004 shows that this method based on ergonomic criteria and fuzzy logic offers interesting perspectives to design good user interfaces. Using this method we identified problems related to three ergonomic criteria: “Visibility of system status”, “User control and freedom” and “Help users recognize and diagnose errors”. These specific problems should be investigated in order to implement design modifications to improve usability. This means that this evaluation method is a proactive tool to provide a basis for checking usability of medical device interfaces. As suggestions for future research, we highlight: (1) the development of a computational system in order to automate the use of the method to evaluate an interface online; (2) the periodic application of the method to estimate how new corrective actions change usability levels.

5. ACKNOWLEDGMENTS

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