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Design and experimental evaluation of an interactive system for pre-movement time reduction in case of fire

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ABSTRACT

After hearing a fire alarm, people continue to carry out activities not directly connected to the evacuation procedure: this pre-movement phase could be very long, especially when people are involved in carrying out their working activities and in using their electronic devices. Starting from this problem regarding safety, our study proposes a system for reducing pre-movement time that is based on an interaction with the people being evacuated. The system, composed of individual wearable devices, is organized in two modules: the first is the Zig-Bee-based localization module which identifies people's positions after the alarm and understands whether they are evacuating; the second is an interactive module which gives a personal stimulus to latecomers. This system was tested for university building evacuation. A case study has been analyzed, which also compared experimental results to those of simulation software. The simulator was able to reasonably reproduce the real phenomenon. The effectiveness of the system was investigated through simulations by considering different individual responses. Our results demonstrate that up to 30% reduction in total evacuation time can be obtained.

1. Introduction

Several studies in the past have been conducted on social and environmental factors that influence the "evacuation time" of a building during a fire [1–7]. In particular, real accident analyses have shown how the first evacuation phase influences the total evacuation procedure [1,3]: this so-called pre-movement phase [8] delays the start of evacuation and can often lead to numerous losses of life [8–10], especially when people are involved in carrying out their work activities or in using their personal devices. The correct designing of architectural spaces is an essential element for aiding evacuation [5], but it becomes very important to efficiently project devices that are able to help people in the evacuation process and especially in the pre-movement phase [5, 11]. Similar systems can be composed of personal devices [12] based on the recognition of wrong and time-wasting behaviours: they can interact with people in order to effectively reduce the egress time whereby increasing the level of safety of the building itself [13]. The definition of such an interactive system for reducing pre-movement time involves two main factors. The first factor concerns behavioural aspects and human phenomena during evacuation especially in the pre-movement phase [8,11,14]. In this work, the attention is focused on buildings where people were involved in working and studying activities and in using their personal electronic devices (i.e., university) [14]. The second factor involves defining a system that is able to identify wrong behaviours and to interact with people in order to increase their level of safety.

Regarding the first factor, the pre-movement phase [15–18] starts after fire is detected and the occupants are alerted. In this phase, people do different things before moving out [8,19]. For instance, they take time trying to interpret any information announced about dangers, interact with other individuals around them [6,8,13], wait for other people such as their friends or relatives or other people they know ("attachment to people" phenomenon) [6] and try to collect their belongings ("attachment to things" phenomenon) [20]. The quantitative and qualitative characterization of this phase is analyzed for different buildings and situations: offices [21], stores [22], hotels [11], cinemas and theatres [13], schools [14,23–25], flats [26], and care homes [18]. As far as quantification of time is concerned, the maximum pre-movement time measured is equal to 3.92 min for a theatre (after an announcement) [8]. However, these numerical data show wide dispersion, depending on the type of building and activities in which people are engaged [25, 27]. As such, different proposals of time probability distributions have been provided [4,8]. Nevertheless, "attachment" behaviours [16] have not been investigated in detail, and there is a lack of organized data about important conditions in buildings, such as the use of personal

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electronic devices by occupants of schools, and universities [14]. In this case, people can be easily inclined to waste time by behaving wrongly like when trying to save their data and personal belongings: the pre-movement time in this situation is very significant, and so its reduction becomes essential in order to improve the whole evacuation process in terms of safety.

As such, some authors have suggested the need to interact with people during an indoor fire evacuation in order to effectively reduce egress time in both pre-movement and motion phases [28]. Consequently, the second factor concerns defining an interactive system for supporting evacuation. Various systems composed of modern and wearable devices have been proposed [12,29–32]; in addition, multi-sensor approaches are provided [33]. Similar technologies have also been proposed for outdoor evacuations [34]. These devices can also be part of complex systems for monitoring evacuation and aiding the occupants [32,34,35]. In particular, a direct and personal stimulus can be introduced and given to individuals that do not move immediately after the communication for evacuation (e.g., the sound of the fire alarm) has been made. Similar systems can be composed of a localization module and an interactive module [12]. Different wireless technologies are often used for the localization module [12,33,36–38]. Wi-Fi location tracker is able to develop fast flow control algorithms for real-time emergency evacuation [39]; modifications in network robustness can be introduced [40, 41]. Recently, CPSs (cyber physical systems) have been proposed as tools to further develop interactions between the physical and virtual world, such as location tracking and road information sensing [42]. The introduction of ERISs (Emergency response information systems) has been suggested to enhance emergency response operations [43]. Another system in real-time building monitoring technologies concerns sensor units and communication network based on wireless Zig-Bee which can also be used in evacuation situations [44–47], such as those for construction elevator security system [48] or patient localization and environmental monitoring [49]. Localization data can be elaborated by different algorithms [32] in order to give information or stimuli to people evacuating (e.g., appropriate evacuation routes) [50–54]. The interactive module effectively returns information and stimuli to the occupants based on algorithm results. The interactive module can be included into common elements, such as way-finding components [31,32] or decision nodes [29], or personal and portable devices [12,32]. The testing phase usually consists in technology effectiveness analysis and in validating the system by using evacuation simulation software.

However, a limited number of studies have used similar systems for aiding evacuation, and only few of them are interactive; finally, there has not been any further development in interaction with people during pre-movement time.

On the basis of the above observations, this work proposes an interactive system for aiding evacuation in a real situation, and in particular, for pre-movement time reduction. An interactive system has been designed: the system can be worn by each person who can take advantage of a wireless network by using Zig-Bee technology. System requirements were experimentally analyzed which concerned localization problems and the response of the system for recognizing wrong behaviours and for interacting with individuals through a direct and personal stimulus. The attention is focused on a possible application of the system in the context of universities and schools where people are usually busy using their electronic devices for learning activities. Experimental students' evacuations from classrooms were analyzed, and quantitative and qualitative behavioural data have been provided; one of the experimental evacuations was recreated through simulation software and results were then compared, demonstrating the possibility to simulate a real case through the software. Finally, the effectiveness of the system in terms of technological aspects, such as possible interferences, has been evaluated; then, the evacuation time reduction by using the simulator is analyzed.

2. Phases and methods

2.1. Phases

The study was organized in the following four phases:

1. The interactive wearable system was designed for pre-movement time reduction and evaluation of technological requirements.
2. Experimental evacuations of university classrooms were carried out while personal electronic devices were being used.
3. The correspondence between experimental evacuations results and simulations using software was tested.
4. The system was evaluated in terms of evacuation time reduction by means of simulation software.

In the first part of the study, the interactive system for pre-movement time reduction was defined, including module characterization. The system was capable of recognizing defined “wasting-time” behaviours and was able to interact with students in order to reduce the fire evacuation time. The evaluation of technological requirements has been provided.

Since a particular environment for testing our proposed system was needed, the evacuation of a school building was chosen, and in particular, university classrooms [14], keeping a special eye on the pre-movement phase. In these classrooms, students were using their personal electronic devices (laptops, tablets) during their regular educational activities: the use of these devices can modify their evacuation behaviours and consequently, the students' evacuation time. For these reasons, pre-movement time could be very high with respect to other building types. The second part involved various evacuation experiments: in these cases, students did not use our system. Experimental data have been provided in order to classify people in terms of their behaviours during evacuation, define time-wasting behaviours, and to quantify students' pre-movement time.

Then, the goal was to evaluate the effectiveness of our system in the selected environment. A series of real devices was not actually assembled, and consequently simulations for this testing phase were used. Since a validation test of the simulation software was required, at first, one of the experimental evacuations was recreated through simulation software. Later, results were compared to those of the real evacuations. The correspondence between the real phenomena and the simulated ones is positive, and so it is possible to use the simulation software for the testing phase.

Finally, in the fourth phase, the effectiveness of the proposed system is verified through an evaluation of the effective reduction of the evacuation time in the case study using the simulation software.

2.2. Methods

2.2.1. Interactive system architecture

The architecture of our interactive system is designed with the purpose of recognizing the “wrong” pre-movement behaviours that are experimentally noticed and of giving a direct stimulus to them by means of some wearable device. The general characteristics of the system have been roughly determined on observations of previous literature. The proposed system is composed of a *localization module* for tracking the positions of individuals and an *interactive module* with a vibration motor for interacting with people through a direct and personal stimulus. The hardware platform used was the CC2431DK platform produced by Chipcon [55]. This platform uses a wireless network based on the ZigBee-2006 standard. The CC2431 chip includes a location detection hardware module that can be used in the so-called blind nodes (i.e., nodes with unknown location) to receive signals from nodes with known location. The location engine calculates an estimate of the blind node's position that is based on the value of Received Signal Strength Indicator (RSSI). Through an appropriate configuration of the 21 general I/O CC2431 pins and a programming activity, the system is