Improving Emergency Response to Mass Casualty Incidents

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Abstract

Mass causality incidents generate a sequence of response events from the emergency services, requiring the allocation and use of resources in a timely fashion. In this paper we describe a system that helps emergency response services optimize their efficiency and coordination. The prototype we have developed provides an early assessment of the health condition of victims in mass casualty incidents, such as in a metro terrorist attack scenario. Our system utilizes information retrieved from passengers' wearable or mobile devices for carrying out such an assessment. Additionally, we describe how we evaluated and optimized our system. Our main contribution is the enhancement of the existing emergency response process for mass causality incidents through the use of Pervasive Computing technology.

1. Introduction

According to the Terrorism Incident Database maintained by the Memorial Institute for the Prevention of Terrorism (MIPT) [1], in the last decade there have been 882 incidents, 6,924 injuries and 2,062 fatalities attributed to terrorist attacks on transportation systems worldwide. Of those attacks, 39% were carried out in subways, trains and stations [2]. Such systems are inherently vulnerable due to the very nature of their design and operations, characterized by high passenger flows and fixed routes with predefined stops. The experts' consensus is that it is virtually impossible to defend against a random attack on passenger systems [3]. Instead, transit agencies have focused on containing the harm of an attack.

Recently, pervasive technologies have been used for assisting people in emergency situations [4,5,6]. Work in this domain has demonstrated that the process of an emergency response, in the context of a car accident scenario, can benefit from the use of pervasive technologies [5,6].

In this paper, we improve the emergency response process by means of pervasive technologies in the context of a metro terrorist attack. We built and evaluated a prototype, employing mobile and wearable devices carried by passengers, which performs an early assessment of victim's health condition during a mass casualty incident. In Section 2 we present background work related to the use of pervasive computing in emergencies. In Section 3 we examine the mass causality emergency response process and identify the potential benefits of developing a pervasive emergency response system dealing with terrorist bombings in a carriage of the metro system. In Section 4 we present the proposed system architecture and describe our prototype in more detail. Furthermore, we evaluate the design of our system, and identify the parameters for improving its accuracy and results.

2. Background and related work

Pervasive Computing applied in emergency situations, more specifically to support the emergency response process, is recent in the literature. Some work has focused on enhancing the existing emergency response mechanism in the context of automobile accident victims. Tognalli [5] elaborated on the technical feasibility of using multi-agent systems on a heterogeneous distributed environment for aiding the ambulance controller who, equipped with Java-compliant cell-phones, is able to book specialists, and to find and query nearby hospitals. Further on, Kalasapur et. al. [6] describe a scenario in which the inner infrastructure of the car is populated with techno-rich computational devices and sensors which, in case of a crash, is able to assess the health status of the passenger and, subsequently, automatically contact emergency response services according to the situation.

However, when aiding users in mass casualty events, such as accidents or attacks on public surface transportation services (buses, trains or metros), the focus of the emergency response process changes shifts from the individual to the affected population as a whole. Thus, the overall goal of treatment changes from the greatest good for each individual to the greatest good for the greatest number [7]. The number of victims may be such that the casualty burden might exceed the personnel's capabilities and medical resources [8]. The potential of utilizing more sophisticated emergency response apparatus embedded into public transportation vehicles becomes greater when considering the increased threat to human life originating from terrorist attacks targeting the public transportation worldwide.

There is a general consensus among mass transit officials and transit security experts that passenger rail systems are inherently vulnerable and thus virtually impossible to defend against attack, due to the very nature of their design and operations [3,9]. Characteristics that ensure the vulnerability are:

- scheduled stops along fixed routes;
- operations depend on people having quick and easy access to stations and trains; and
- the number of access points and volume of ridership make it impractical to subject all rail passengers to the type of screening that airline passengers undergo.

Due to the limitations imposed by the rail system's vulnerability in preventing a random attack, transit agencies have focused on containing the damage resulting from an attack [3]. In this sense, benefits from the use of Pervasive Computing principles may be brought to the context of the emergency response process in a metro attack scenario.

2.1 Emergency response process

The process of emergency response for a mass causality incident, known as the *casualty sequence flow*, consists of:

- rescue and decontamination,
- triage (counting and sorting) of patients,
- stabilization,
- evacuation, and
- definitive treatment [7].

Assessing the number of victims and their condition, referenced to as *scene assessment*, occurs during triage, and is of great importance as it triggers a chain of events in the medical and resource coordination. A Triage Officer, responsible for coordinating the assignment of Triage Teams of emergency medical first responders, conducts initial triage by attaching red, yellow, green or black colored paper triage tags to patients based upon assessed priority. Each of these tags signifies the following:

- red: highest priority treatment as the patient cannot walk and shows abnormal respiration, pulse, or mental status;
- yellow: delayed priority in which the victim cannot walk but presents normal respiration, pulse and mental status;
- green: lower priority in which the patients are injured but able to walk;
- black: no priority for treatment as they present no vital signs.

These activities are performed upon the arrival of the specialized emergency medical first responders' team in the incident scene. Recent research improves upon the paper triage tags through the use of electronic tags, employing tag readers, passive RFID tags and PDAs to collect data about the mass casualty events [10,11,12,13,14,15].

Rapid and accurate triage is essential to minimizing mortality among survivors. It has been established that mortality among critically injured survivors of terrorist bombing disasters is directly related to the magnitude of *overtriage* (noncritical injured assigned to immediate care) [16,17]. The authors in [16], by analyzing 220 major worldwide incidents, demonstrate a direct linear relationship between overtriage and critical mortality (the percentage of deaths among only the critically injured survivors). This direct relationship suggests that bad estimates in the health condition of patients results in patients dying. This may be attributed to the fact that an overestimation leads to a stretching of available resources, which subsequently results in not giving enough attention to those who actually require it.

An early scene assessment can help optimize resource allocation and utilization by the various emergency services (estimated number of specialized personnel required, number of ambulances, amount of beds in hospitals, etc). As a consequence, it also helps in saving time in the sequence of events, which has been shown to reduce the overall critical mortality rate (the percentage of deaths among only the critically injured survivors) [8,18].

To illustrate this point, in Figure 1 we show the resource allocation and patient flow inside hospitals as a function of time during the London Bombings of July 27th 2005 [19]. The horizontal axis in this figure is time, while the vertical axis identifies the various locations (top of graph) or various patients (middle and bottom) who were treated. For each patient we are able to identify the time of their arrival at the hospital, as well as the time at which they moved from one stage of treatment to the next.

From the graph we can see that due to the sequential flow of victims, the hospital prioritized treatment according to the victims' order of arrival. Thus, while some victims were being operated on, others where just arriving at the hospital. Under such conditions, it becomes crucial that the first victims to arrive at the hospital are the ones who require the most urgent attention.

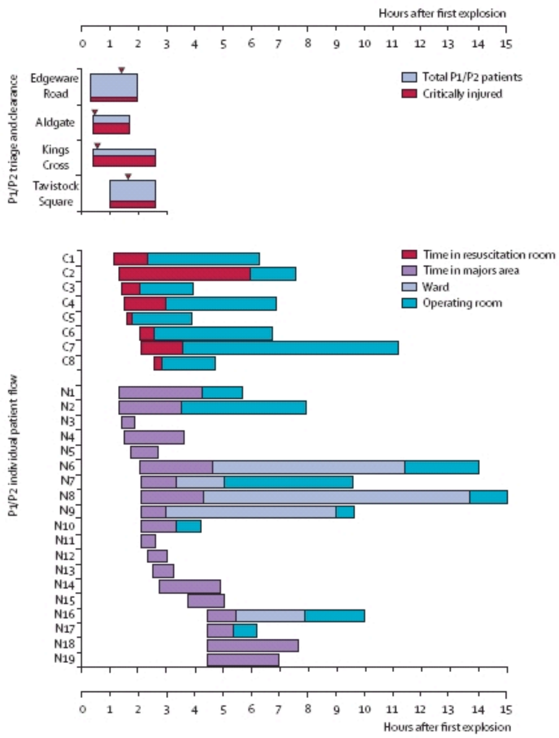

Figure 1. Patient flow and surge analysis on London Bombings July 7th, 2005. *(up)* Emergency service arrival and scene clearance times for each site, and *(down)* patient flow through emergency department and operating rooms.

Considering the conditions under which triage and treatment take place, here we focus on providing an early assessment and early warning of the number of victims that the emergency services and hospitals can expect. Specifically, our work focuses on the use of everyday mobile/wearable devices (such as PDAs, cell phones and wristwatches) as a complementary tool for enhancing the response process of a terrorist attack against the metro system. Through the information retrieved from these devices, which follows a modified Simple Triage Rapid Treatment (START) [18] scheme, our system generates estimations on the number and condition of the victims before the arrival of the first responders on the scene of the incident.

3. Proposed mass causality emergency response environment

To improve the process of mass casualty emergency response, we propose using Pervasive Computing technologies to gather additional information about the incident and passengers' health condition. Central to our scheme is the augmentation of metro carriages such that they can detect abnormal events, such as a bomb blast. This can be achieved using dedicated sensors in each carriage. Additionally, communication channels are required in each carriage in order to enable information retrieval from the passengers' mobile devices. Health condition information, following a modified START [18] scheme, retrieved from passengers carrying mobile/wearable devices (e.g., wristwatches, smart phones, PDAs, etc.) can be used for further estimations on the number and condition of victims for the whole affected population. In this way, a first assessment can be made soon after the attack takes place, and can lead to gaining time in the causality sequence flow.

Our proposed pervasive metro emergency response environment is visualized in Figure 2. The figure highlights three fundamental components:

- *P*eak overpressure sensors, responsible for monitoring bomb blast events. These sensors must be installed in carriages and platforms, and they can trigger an emergency procedure should they detect a bomb blast.
- Local connectivity, which allows passengers' devices to be authenticated and queried in case of an event. This may be implemented using Bluetooth, WiFi, or any other proximity technology.
- Mobile and wearable devices carried by the passengers. These devices query the passengers about their health, and relay the response to the carriages' computational infrastructure.

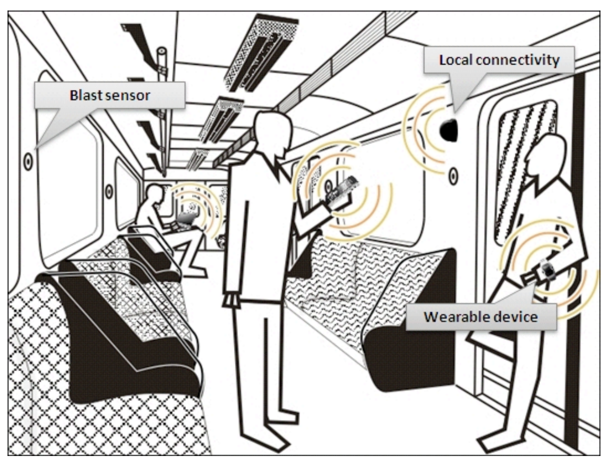

Figure 2. Pervasive metro emergency response environment.

3.1. System architecture

Our system has a multi-agent architecture. Agents are divided into the following categories:

- Personal agents, running on mobile devices carried by passengers and by the train master.
- Environmental agents, responsible for managing the train schedule stops, for aggregating, estimating and interpreting data gathered from sensors (also, called Context Server agents), for keeping track of passengers' entry and exit, and for intercommunicating with each other to collaboratively achieve pre-defined response tasks.
- Emergency service agents, which act as interfaces between, e.g., the ambulance service center system and environmental agents. The design of the proposal is depicted in Figure 3.

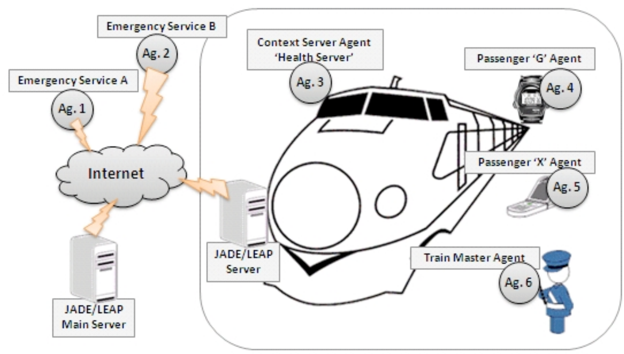

Figure 3. Metro emergency response system employing a multi-agent architecture.

There are two types of personal agents. The first type is installed and maintained on mobile devices carried by train master/drivers (Ag.6, *TrainMasterAgent*). These agents inform the train master/drivers when abnormal events are detected by the sensors appended on the metro carriages. The agent initially requests the drivers' evaluation of the situation according. When the agent receives a response, or times out, the event is assessed as true or false, e.g., whether a bomb blast had occurred or not.

A second type of personal agent is the one installed on the passengers' mobile/wearable devices (Ag.4 and Ag.5, *PassengerAgent*). Its role is to assess the passengers' health condition (and relay this information to the proper agent). This only happens when the train driver evaluates the alarm as real, or the driver did not reply to the TrainMasterAgent.

Similarly, in respect to the environmental agents, we have identified two main agent types. One, which controls and coordinates the execution of environmental-related agents' tasks in order to achieve the completion of higher level response tasks. In our proposed scenario, such agents coordinate the required subsequent steps that lead to the early scene assessment, i.e., monitoring of data from sensors, alerting train drivers, gathering health condition information from passengers and, estimating number and condition of victims. The agent implemented for this purpose (*TrainAgent*) also manages train schedules, authenticates new boarding passengers and discards old authentications.

The second type of environmental agent is the one that acts as *Context Servers*, which in the scope of our work correspond to agents that are able to gather, aggregate, interpret, estimate and store data information from sensors or other monitored agents. After aggregation and interpretation, the data is converted to *high level context* information, e.g., peak overpressure data received from blast sensors over a threshold of 0.15 psi, sufficient pressure to break window glass [20], are considered as an abnormal event. To retrieve information from such agents, we have implemented two approaches. The *publish-subscribe* approach, in which agents subscribers are automatically notified after context changes events, is used by the *AbornamlityCServerAgent* for notifying subscribers as soon as an abnormal event is detected. And the second approach is the *force context update*, in which a Context Server agent pushes updated information from sensors or from other monitored agent. This last approach is used by the *HealthCServerAgent* for forcing health information retrieval from passengers after a bomb blast occurs.

3.2. Prototype

To evaluate our system we have developed a working prototype. Our prototype employes the agents described in section 3.1. The agents and their intercommunications were designed and implemented by employing the multi-agent JADE [21]/LEAP [22] platform. Environmental agents were implemented with the JADE platform and were hosted on main-container deployed on a Windows machine. Personal agents, implemented with the JADE/LEAP combination, run on he J2ME CDC implementation provided by IBM's WEME J9 Virtual Machine [23]. For our tests, we used Softbank X01HT cell phones equipped with Windows Mobile 5.0. Local wireless connectivity, to bridge the connection among personal agents and environmental agents, was established using the IEEE802.11b/g standard.

3.2.1. START-based triage scheme

The original START scheme [18] is performed by medical responders (through, or not, the help of specialized sensors) who first attend the scene and have the ability to ambulate respiration, pulse and mental status of the victims. Patients are labeled with different colors which represents different treatment priorities: *(i)* RED, priority treatment as the patient cannot walk and shows abnormal respiration, pulse, or mental status; *(ii)* YELLOW, delayed priority in which the victim cannot walk but presents normal respiration, pulse and mental status; *(iii)* GREEN, third priority and copes with the injured who are able to walk; and *(iv)* BLACK, are the ones that have no priority for treatment as they present no vital signs.

Our approach relies on a START-based self-assessment scheme which can be performed through the use of everyday mobile devices like PDAs, smart phones, cell phones and wristwatches. The *PassengerAgent* agent embeds the code for self-assessment. The main goal is to perform an overall and non-time consuming assessment of the passengers' health condition by employing symptoms-related instructions and questions. An emergency situation is generally characterized by its impact on peoples' physical and psychological well-being, which imply that such assisting tool should be easy for the person to use and should not require much thinking or complicated actions.

Therefore, the assessment instructions and questions were made as simple and comprehensive as possible. "*Are you injured?*" assesses whether the person was affected by the blast or not; "*Are you able to stand and walk?*" assesses whether the person must be tagged as GREEN or should proceed. "*Is your breathing impaired?*" and other symptoms-related questions such as *"Do you feel dizzy, weak or nauseous?"* and *"Is your skin clammy?"* helps assessing whether the person must be tagged as YELLOW (apparent normal pulse and normal breathing are presented) or RED (apparent abnormal pulse or breathing). The mental status is verified by the person's ability to respond and follow the instructions.

The personal agents' graphical interfaces are shown in Figure 4. On the left side, the *PassengerAgent* GUI, designed to perform a START self-assessment, running on a PocketPC emulator is shown. And on the right side, the *TrainMasterAgent* GUI running on a Softbank X01HT cell phone is displayed.

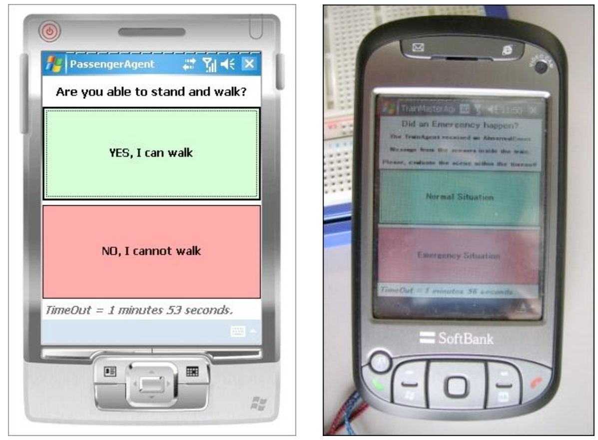

Figure 4. *(left) PassengerAgent* GUI running on a PocketPC emulator and *(right) TrainMasterAgent* GUI on a Softbank X01HT cell phone.

3.2.2. Agents' design and intercommunication

The agents were designed according to the behaviors described in section 3.1. The *TrainAgent* agent coordinates the execution of other environmental-related agents in order to achieve the response. Figure 5 presents the intercommunication flow and actions diagram performed by the agents which are coordinated by the *TrainAgent*. The ellipses are the states assumed by the corresponding agents. The text above the arrows are events and the text below them are actions taken in response to the events to change from one state to another.

As soon as a passenger, carrying a mobile device IEEE802.11 enabled, boards a carriage, his agent is started and is automatically connected to the JADE container within the infrastructure of the carriage. It, then, authenticates itself with the *HealthCServerAgent* agent.

As shown in Figure 5, once an overpressure peak is detected, indicating a probable bomb blast event, by the *AbornamlityCServerAgent*, a (context changed) message is sent to the *TrainMasterAgent* which requests the train driver to evaluate the veracity of the event. If the event is assessed as true or if he does not respond within a timeout, the *HealthCServerAgent* forces a context update, i.e., it triggers messages requesting self-assessment of the passengers using the START-based triage scheme described in section 3.2.2. Subsequently, given the response types and the number of replies, an estimation of the whole population is can be performed, see section 3.3. Finally, the *TrainAgent* contacts the adequate emergency service.

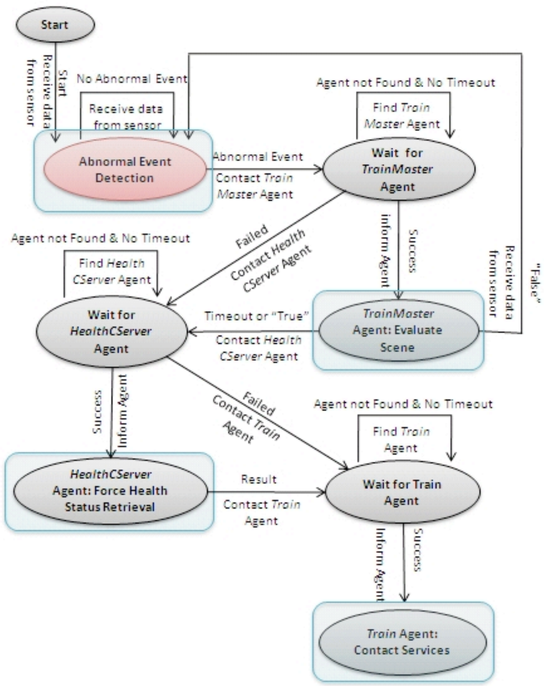

Figure 5. Communication flow diagram.

3.3. Evaluation

In this section we analyze the necessary parameters for achieving accurate estimations by our system. While we intend to carry out a real-world study of our system, such a study is quite expensive to prepare and carry out. So far we have focused on developing a simulation environment which we can use to assess the effectiveness and accuracy of our system under a range of circumstances.

For simplicity purposes, we assume that local connectivity is available even after a bomb blast occurs. To carry out our initial evaluation, we employed a custom modeling and simulation environment developed using Java. The specification of the simulation parameters and constraints are as follows:

- each carriage has 200 passengers;
- passengers carrying mobile devices are distributed uniformly; their number is the *sample size*;
- after an emergency occurs, a portion of passengers possessing mobile devices may respond, thus defining the *response rate*;
- each response, representing the victim's condition, can be one of: OK, GREEN, YELLOW or RED;
- the number of non-responses is obtained by subtracting the number of responses from the sample size, and is used as an error factor applied over the number of YELLOW, RED and assumed BLACK victims;
- it is assumed that an emergency officer will be responsible for assuring that all victims that are not severely injured (OK or GREEN) will retrieve their health information at site or at specialized booths.

3.3.1. Results

For our evaluation, we varied the sample size from 12.5% to 100% of the whole population. Additionally, we explored different possible response rates, considering 25%, 50%, 75% and 100% over each possible sample size. Figure 6 shows the error margin, calculated by using 95% confidence interval, for a single response category (e.g., number of GREEN victims) for 0% to 100% of response rates. Furthermore, Figure 7 shows the variation of the overall error margin based on different sample sizes.

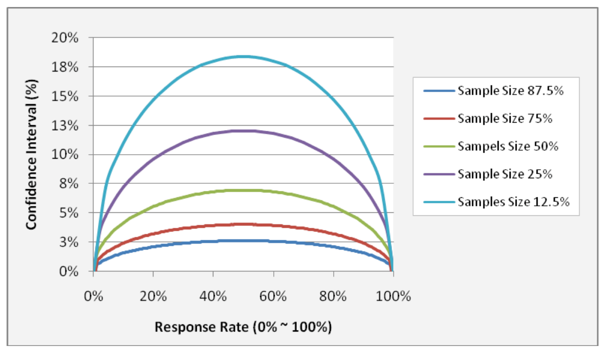

Figure 6. Confidence interval *versus* response rates for a single category (e.g., #GREEN).

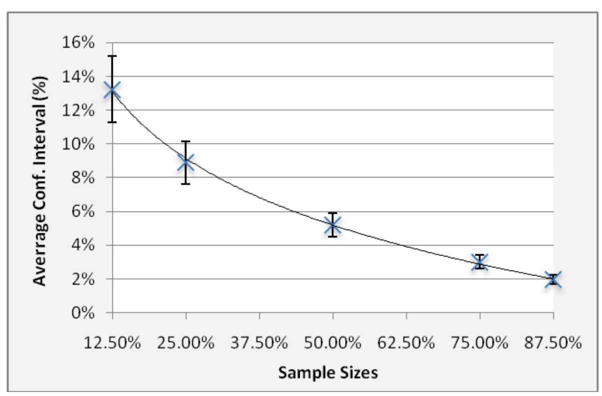

Figure 7. Average confidence interval *versus* sample sizes over an average of all response rates.

Additionally, we ran through specific simulation scenarios where, for example, the actual number of passengers falling in each category was as follows: 50% OK, 5% RED, 10% YELLOW and 35% GREEN over different response rates. Considering 25% and 75% response rate from different sample sizes in such an accident is shown in Figures 8 and 9 respectively.

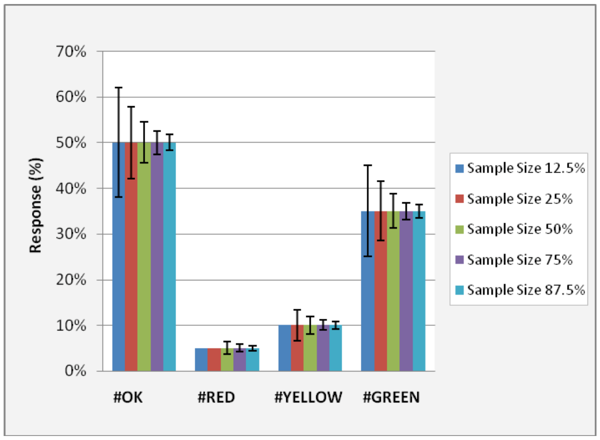

Figure 8. Error margin for 25% total response rate: #OK (50%), #RED (5%), #YELLOW (10%) and #GREEN (35%).

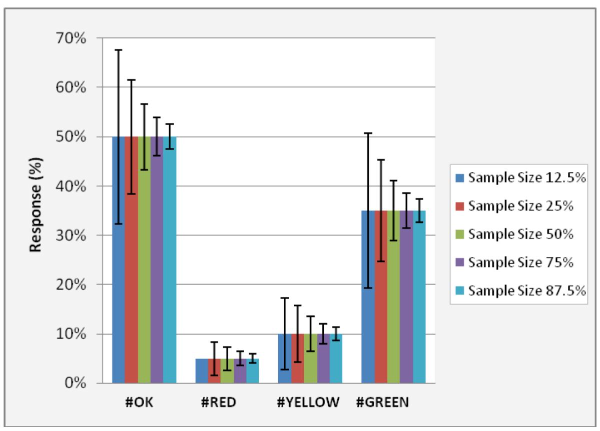

Figure 9. Error margin for 75% total response rate: #OK (50%), #RED (5%), #YELLOW (10%) and #GREEN (35%).

3.3.2. Discussion

In Figures 6 and 7 we are able to identify the accuracy of our system, regardless of the actual numbers of victims and their condition. It is important to note that, as shown in Figure 6, a higher response rate for a single response category (e.g. the number of GREEN responses) does not necessarily decrease the error margin our system's assessment. While an increase in sample size results in gradually smaller error margins, and increase in response rate for a specific category can result in a small increase in that categories error margin. In other words, if almost everyone, or almost noone, says they are OK, then we are pretty confident about how many people are OK. If, however, we have a 50% response rate, then we are faced with more uncertainty, hence the slightly higher error margin. Strictly speaking, the error margin peaks when the sample size reaches 50% of the response population.

However, higher sample sizes result in smaller error margin and, therefore, an increased accuracy of the estimations provided by our system. This is more clearly shown in Figure 7, where we provide an overview of the overall error margin given different samples sizes. For instance, given a sample size of 87.5%, the overall confidence interval of our systems' estimation decreases to 2%. On the other hand, a sample size of 12.5% gives a confidence interval of 13% with 2% standard deviation. The lack of information lasting such a case will, most probably, be inadequate in aiding the response process.

In the simulation where the actual number of passengers falling in each category was pre-defined, given overall response rates of 25% and 75%, in Figures 8 and 9 we present the error margin for each variable. We see that the error margin increases as the response rates get higher. This is due to the fact that the response rate for each individual category is situated before the first half of curves shown in Figure 6, hence the error margin goes up as the overall response rate goes up (50%). It is also important to notice that the error margin increases more abruptly for smaller sample sizes. Although the error margin, calculated with 95% confidence interval, may increase according to the response rate, keeping to higher sample sizes shorten the error margin slide window, and thus increases the overall accuracy.

Our results suggest that if percentages of each category (OK, RED, YELLOW, GREEN) are distributed relatively evenly, the accuracy of our system is compromised. On the other hand, should there be one category with most passengers (e.g. OK), then the accuracy of our system is strengthened.

We should also point out that while sample sizes and response rates may seem arbitrary measures, in fact they can provide concrete guidance in commercializing our system. Given known statistics about the penetration of specific technologies in the general population, authorities can make a more educated decision about which devices they decide to support. If, for instance, we know that about 10% of passengers have Bluetooth devices, then we also know that 10% is the potential maximum sample size our system can expect if an attack takes place.

4. Final considerations and future work

In this paper we present a prototype for enhancing the existing emergency response process in the context of a metro/subway attack. In the existing literature it is clear that any system that provides an early assessment of the damage and status of victims can greatly improve the efficiency of emergency responders. Our aim has been to develop a system that provides a quite early assessment of the extent of damage, even before first responders and officials arrive at the scene of the attack or accident.

Our prototype was implemented using a multi-agent architecture in which the agents cooperate in order to assess the number of victims and their health condition. Our results demonstrate that the accuracy of our system's estimations depends on passenger sample size and response rates. This knowledge enables us to assess the quality of our systems estimations, and decide if they do or do not assist emergency services during the response process.

As a note, we should point out that any simulation-based work may be questioned about its external validity. In our case, a proper evaluation of our system is quite expensive and time-consuming, thus we have opted to initially use simulation to identify emergent properties of our system. As such our work is susceptible to criticism on our assumptions about users' reactions in cases of emergency. Placed in an emergency situation, will users answer truthfully and correctly, or will they be prone to overestimate/underestimate their condition? Such questions cannot be answered through mere simulation, but only through a thorough evaluation involving real users. Even so, however, it is quite difficult to carry out a user study exploring user responses under threat, given that as researchers we cannot put our users under real threat.

So far, in our work we have identified the behavior and accuracy of our system, under different conditions and assuming rational user responses. The logical next step for us is to identify and accurately model user responses in situations of extreme stress, threat, and danger. An ongoing challenge is establishing such reactions in a controlled lab experiment.

Finally, we are currently incorporating in our system's assessment the ESCT indoor blast model, designed by the US Department of Defense Explosives Safety Board. We intend to use this model to optimize the error factors applied over the number of BLACK , RED and YELLOW victims in our system's assesment.

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