Algorithmic State Machine Design for Timely Health Emergency Management in an IoT Environment

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Abstract: In emergency cases related to massive accidents, environmental disasters, and war time, health professionals face considerable challenges due to the high number of patients who are in need of emergency treatment. Research works attempt to propose effective in-hospital and pre-hospital smart emergency systems to reduce the mortality rate among the patients who desperately wait to receive appropriate care. This paper presents a model of a timely prehospital emergency management system that can be implemented as an interface to an Internet of Things (IoT) environment. This work presents the necessary stages for prehospital emergency environments, where many factors may make the timely management of emergency systems very difficult. The proposed model is based on an Algorithmic State Machine (ASM) that can be implemented in either hardware or software, providing an embedded system interface for IoT. Moreover, this paper provides a timing analysis for either a single emergency event or multiple simultaneous emergency events. Embedded systems' developers can use the proposed model to produce an appropriate prehospital smart emergency solution.

1 INTRODUCTION

Emergency care is a right for everyone in need of urgent treatment. Elderly with dehydration symptoms, persons facing a heart attack, pregnant women who are about to deliver a baby, passengers bleeding due to car accidents or airplane crashes, a population hit by an earthquake or a tsunami, and citizens wounded from bomb attacks are all examples of patients who absolutely need quick treatment to save their lives.

Emergency services should start on the site of disasters or any health-threatening events, en route to hospitals, and on the arrival to hospitals up to admission, diagnosis, and treatment. In all these stages, health professionals face timely challenges to quickly provide emergency care to save patients' lives. Despite the considerable emergency effort, the mortality rate among those patients can be very high even in the absence of major disasters. For example, a study finds that the death rate in England is higher for the emergency patients admitted to hospitals at the weekend than for the patients admitted on weekdays (Meacock et al., 2017).

Despite the introduction of a four-hour rule to discharge emergency patients in some hospitals, in order to reduce patient waiting times and mortality rates, the quality of care received by patients during this four-hour period was questionable (Crawford et al., 2014).

In cases of environmental disasters, the challenges of emergency service provision are considerably high. For example, in the case of the earthquake that hit Haiti in 2010, communication difficulties were among the primary challenges of providing emergency services to displaced persons (Magloire et al., 2010).

With the advances in modern technologies in general, and in wireless communications and Internet of Things (IoT) in particular, smart emergency systems were proposed to mitigate the mortality rate among the emergency patients. This paper presents a model of a prehospital smart emergency system that can be invaluable toward the achievement of efficient management of such systems. The presented system model includes timely information that can be implemented even if multiple health-threatening events occur simultaneously.

Taking into consideration that timely data is recorded for each health-threatening event in prehospital stages, the presented model fits well as an interface between the recorded timing data and IoT-based emergency response devices/robots/vehicles/systems,

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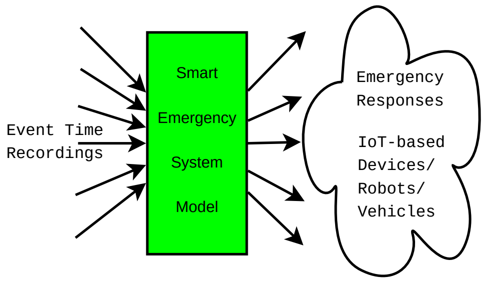

Figure 1: The Model as an Interface for a Prehospital Smart Emergency System.

as depicted in Figure 1.

In literature, researchers focus on enhancing prehospital solutions through wearable devices and communication technologies (Seneviratne et al., 2017) (Wu et al., 2017) (Amato and Coronato, 2017).

On top of wearable devices, (Yu et al., 2018) propose a personalized scheme for predicting the elderly's wellness condition ahead of time, by collecting data from multiple monitoring devices, integrating the collected data, and improving the prediction via statistical learning. In another healthcare prediction approach, (Park et al., 2018) propose a prehospital care recording system as a result of the integration of patients' personal lifelogs and electronic medical records, in addition to ambulance monitoring of patients.

(Chiou and Liao, 2018) highlight the importance of minimizing the time of rescue response in the case of incidents, and propose the usage of mobile devices and a central server, which can alert medical staff in the incident region and provide clear directions to the incident location.

In all proposed solutions, prehospital timely tracking of health cases is implied. Practically, such solutions should be coupled with a timely emergency management that can be effectively implemented in an IoT environment.

Integration of such technologies in the IoT environment would need hardware-based computation element (Al-Fuqaha et al., 2015), such as microcontrollers, microprocessors, Field Programmable Gate Arrays (FPGAs), and Systems on Chip (SoCs). Therefore, the presented model can be implemented in hardware using, for example, a Hardware Description Language (HDL) and FPGAs (Brown and Vranesic, 2014), in order to establish a solid emergency management system.

Prehospital timely emergency management has not been studied extensively despite its considerable importance. The authors of (Wu and Ren, 2016) point to emergency management stages in the civil aviation, taking into consideration prevention, preparation, response, and recovery. However, it was not clear how such stages can be implemented, in order to improve emergency management in general, and in the context of IoT in particular.

In (Manley et al., 2016), the authors present a study of timely emergency evacuation using an agent-based model, where the study focuses on evacuation planning from an airport terminals.

In contrast to existing models, our presented ASM-based model can be implemented in either hardware or software and integrated into an IoT-based smart emergency system, for the ultimate purpose of greatly reducing the prehospital mortality rate.

The contributions of this paper can be summarized as follows:

- Prehospital emergency timing model based on ASM is presented.
- The model can be implemented in either hardware or software.
- The model can be an interface to an IoT environment.
- A timing analysis of a single occurrence of an emergency event is provided.
- A timing analysis of the simultaneous occurrence of multiple emergency events is provided.

The following sections of this paper are organized as follows. Section 2 describes the stages that typically feature in smart prehospital emergency systems. Section 3 presents the proposed model based on an algorithmic state machine. Section 4 provides a timing analysis of prehospital smart emergency systems for either a single health-threatening event or multiple events. Section 5 includes further discussions. Finally, section 6 concludes this paper.

2 STAGES OF PREHOSPITAL SMART EMERGENCY SYSTEMS

Smart emergency systems imply the use of many technologies, tools, and equipment through stages of prehospital and in-hospital healthcare. First, the detection of a health-threatening event once it occurs, and the notification of such an occurrence, should be quickly accomplished through specific technological equipment. Second, the dispatch of appropriate rescue vehicles, health professionals, and appropriate tools, should be the next immediate step in order to save lives as quickly as possible. Third, the use of effective equipment is important to establish communications between dispatched personnel and in-hospital personnel, in order to inform the hospital ahead of time about the patients' status. Fourth, hospitals should be well-prepared to receive the emergency patients, diagnose them, and admit them accordingly. Taking into consideration that some patients may seek emergency care without any prior communications, hospitals should be able to efficiently handle unpredictable cases.

Figure 2 depicts a visual diagram showing eight stages of a typical prehospital emergency system, from the occurrence of a health-related event up to patient's arrival to the hospital for emergency care. The sequence of stages starts with (1) event occurrence, (2) detection, and (3) notification, followed by (4) dispatching of rescue team who shall have the purpose of prompt (5) arrival to the event's site. Subsequently, (6) on-site care shall take place prior to (7) taking casualties to the hospital up to (8) the arrival to the hospital, where some waiting time may happen before the actual in-hospital emergency care.

The main aim of the proposed solution is to model this timely sequence in an implementable way that can be well interfaced to an IoT environment.

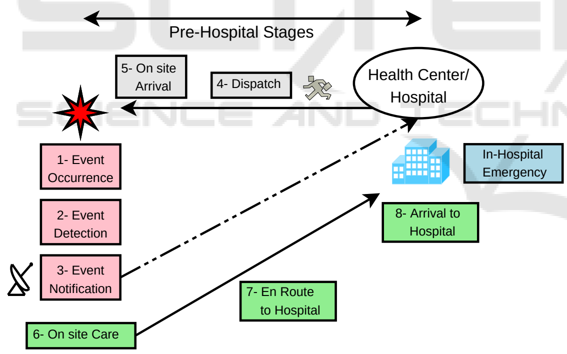

Figure 2: Stages of a Typical prehospital Emergency System.

3 PROPOSED ASM-BASED MODEL FOR PREHOSPITAL STAGES

An informative visual way of representing a prehospital smart emergency system can be shown using an Algorithmic State Machine (ASM) chart as depicted in Figure 3.

Even though the ASM chart looks like a traditional flowchart in terms of the representation of a sequence of states (or stages), system designers con-

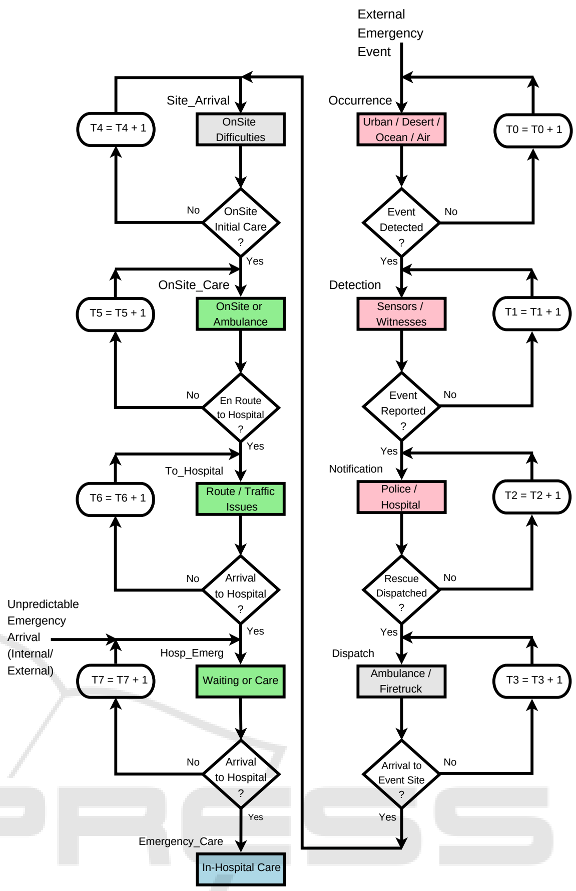

Figure 3: An ASM Chart for a Typical Model of a Prehospital Smart Emergency System.

sider the ASM chart a better way to model sequential stages of a system with implicit timing information (Brown and Vranesic, 2014). When a system must consist of hardware and software together, the ASM chart is particularly important to import timely information into hardware for integration with the IoT environment.

The typical smart emergency system, depicted in Figure 3, includes eight prehospital states before the start of the in-hospital emergency care, where each state is associated with a timer indicating the length of time the system stays in the corresponding state. The least length of time accumulated through all eight timers, the quickest would be initiating the in-hospital care.

Health professionals should be able to record the duration of each prehospital stage, as a part of an effective management of emergency cases. The stage duration records can be obtained according to the data collected from sensors, cameras, hospital records, ambulance records, police records, and sometimes from media and bystanders.

The first prehospital stage is the occurrence of a health-threatening event. As long as no sensors/witnesses detect such occurrence, the timer T0 in Figure 3 increments and the state “Occurrence" remains unchanged. The location of the event (e.g. urban, desert, or ocean), its sudden occurrence, and the absence of any instant localization methods, would make the event undetectable for quite a long time. Even if the event has been detected (state “Detection" in Figure 3) and notified (state “Notification" in Figure 3), and even if a rescue team is dispatched (state “Dispatch" in Figure 3), the localization of the event may take long time and may even never been reached by the dispatched personnel. Therefore, the system would be stuck at the state “Dispatch" with long duration of the timer T3 (if its limit is not exceeded), until arrival to the event’s site. An example of such an event is the Malaysian flight MH370 that went missing on March 8th 2014, and has never been found after five years of the incident (as of the time of writing this article), despite extensive search efforts in the Indian ocean (Mujeebu, 2016).

Once the occurrence of an event is detected, timer T0 stops and timer T1 starts and increments until notification of the event is performed. Detection of an event can be done through sensors, cameras, or witnesses. Event’s notification may promptly happen, which indicates a short duration of T1, whereas timer T2 starts and increments up to dispatching appropriate rescue measures. Communication technologies used in the notification stage would be based on one of the wireless standards or cellular networks, or even through satellites or optical fibers. Once a rescue team is dispatched with appropriate tools, T2 stops and timer T3 starts and increments up to the arrival to the event’s scene. The arrival to the event’s site marks the end of T3 duration and the beginning of T4 duration. The difficulties encountered on site can be overwhelming, which leads to a long duration of T4. The places hit by an earthquake or a tsunami are examples of overwhelming locations that cause lengthy duration of T4, before any initial care starts on site.

Sometimes, on-site care can be initiated by untrained bystanders before the arrival of health professionals. Even though such on-site care is highly recommended in the absence of trained persons, and can be really critical to save a victim’s life, it is not usually included in the typical emergency system since it is not performed by health professionals. However, if on-site care is established by trained bystanders, arriving health professionals may temporarily rely on such care for some victims, in order to treat other victims at the same time. Therefore, in some circumstances, the stage of initial care on the event’s site performed by bystanders would occur before the dispatch of a rescue team, before the team’s arrival, or after their arrival. Therefore, the timer T5 in the model of Figure 3 does not stop until the victim is carried to a vehicle, such an ambulance, that takes its route toward a nearby hospital.

En route to the hospital, the rescue team in a vehicle or an ambulance would be able to notify the hospital’s emergency personnel of the patient’s health status, using wireless communications. In this stage, the timer T6 in Figure 3 depends on the traffic circumstances and route difficulties, and it only stops when the patient actually reaches the hospital. Subsequently, the timer T7 starts and increments until the emergency personnel start their diagnosis and treatment of the patient.

4 TIMING ANALYSIS OF A PREHOSPITAL EMERGENCY SYSTEM

The ASM-based smart emergency system facilitates timing analysis of the featured stages in order for the management to evaluate the duration of each prehospital emergency case. Such timing information of many cases ensures on-going improvement of prehospital emergency systems.

4.1 Single-event Prehospital Emergency System

The typical prehospital ASM chart presented in Figure 3 is based on each health-threatening event. When a single individual person is involved in the event, the ASM chart identifies the prehospital stages and calculates the overall prehospital emergency duration D, where D is:

$$D = T0 + T1 + T2 + T3 + T4 + T5 + T6 + T7.$$

However, when several casualties resulted from a single event, the timers T0, T1, and T2 (for stages “Occurrence," “Detection," and “Notification" respectively in Figure 3) remain the same as they are common to the event with multiple casualties, and the timers T3 and T4 (for stages “Dispatch" and “Site_Arrival" respectively in Figure 3) are associated with each team dispatched to the same event location, whereas the timers T5, T6, and T7 (for stages “OnSite_Care," “To_Hospital," and “Hosp_Emerg" respectively in Figure 3) can be different for each individual casualty. Therefore, the total emergency event duration can be formulated as a summation of three duration periods T_e, T_d, and T_i as follows:

$T_e = T0 + T1 + T2$: Pre-dispatch duration for an event. The subscript 'e' in T_e is to point to the "event" as this duration is common to the event, with multiple rescue teams and multiple casualties.

$T_d = T3 + T4$: Post-dispatch Pre-initial-care duration for an event. The subscript 'd' in T_d is to point to the "dispatch team" as this duration is for each rescue team dispatched to the same event.

$T_i = T5 + T6 + T7$: Individual initial care for an event. The subscript 'i' in T_i is to indicate that this duration is to be calculated for each "individual" casualty resulted from the same event.

$D_i = T_e + T_d + T_i$: Total prehospital "individual" emergency duration for a single event.

As a more concrete example, assume that two rescue teams are dispatched to a single event, where each rescue team provides initial care to two casualties. As a result, there will be a total of four casualties to receive initial care. Accordingly,

$D_{i_1} = T_e + T_{d_1} + T_{i_1}$ is the prehospital emergency duration of one casualty who received initial care from the first rescue team,

$D_{i_2} = T_e + T_{d_1} + T_{i_2}$ is the prehospital emergency duration of another casualty who received initial care from the same first rescue team,

$D_{i_3} = T_e + T_{d_2} + T_{i_3}$ is the prehospital emergency duration of one casualty who received initial care from the second rescue team, and

$D_{i_4} = T_e + T_{d_2} + T_{i_4}$ is the prehospital emergency duration of another casualty who received initial care from the same second rescue team.

Note that T_e is the same for all four casualties because they result from the same event, whereas T_{d_1} is the same for the first two casualties because they are both rescued from the same rescue team, and T_{d_2} is the same for the other two casualties because they are both rescued from the second rescue team. However, T_i is different for each individual casualty because the needed initial care would depend on individual factors such as the injury seriousness of each injured person.

4.2 General Multiple-event Prehospital Emergency System

The aim of the smart emergency system management is to minimize the prehospital emergency duration D_i for each patient. Therefore, the previous section indicates that the minimization of D_i primarily depends on the fast detection and notification of an event (minimum T_e) and the quick arrival of dispatched rescue teams (minimum T_d).

When multiple health-threatening events occur at the same time, the health professionals face more challenges. Multiple events directly imply more rescue teams to be deployed, especially if a high number of casualties are involved. Based on the ASM chart for a single-event emergency system given in Figure 3, a generalized multiple-event smart emergency system can be visualized as depicted in Figure 4.

This figure shows a hierarchical model of each health-threatening event based on the described ASM (Figure 3), where this hierarchy is replicated for additional simultaneous events.

For n health-threatening events, where r rescue teams are dispatched and p patients are involved is the event, a general timing equation for each individual emergency patient can be formulated as follows:

$D_{i_p} = T_{e_n} + T_{d_r} + T_{i_p}$

The aim for efficient smart emergency systems is to minimize the prehospital duration. Therefore, the target equation for any individual prehospital duration should be:

$D_{i_p} = min(T_{e_n} + T_{d_r} + T_{i_p})$

Referring to Figure 4, where two or more events simultaneously occur, and three rescue teams are dispatched for each event, and just two casualties receive care from each rescue team, the following equations evaluate the prehospital duration for twelve emergency patients resulted from two simultaneous events:

$D_{i_1} = T_{e_1} + T_{d_1} + T_{i_{11}}$ (Event 1, Rescue Team 1, Patient 1 [*abbr. 11*])

$D_{i_2} = T_{e_1} + T_{d_1} + T_{i_{12}}$ (Event 1, Rescue Team 1, Patient 2 [*abbr. 12*])

$D_{i_3} = T_{e_1} + T_{d_2} + T_{i_{21}}$ (Event 1, Rescue Team 2, Patient 3 [*abbr. 21*])

$D_{i_4} = T_{e_1} + T_{d_2} + T_{i_{22}}$ (Event 1, Rescue Team 2, Patient 4 [*abbr. 22*])

$D_{i_5} = T_{e_1} + T_{d_3} + T_{i_{31}}$ (Event 1, Rescue Team 3, Patient 5 [*abbr. 31*])

$D_{i_6} = T_{e_1} + T_{d_3} + T_{i_{32}}$ (Event 1, Rescue Team 3, Patient 6 [*abbr. 32*])

$D_{i_7} = T_{e_2} + T_{d_1} + T_{i_{11}}$ (Event 2, Rescue Team 1, Patient 7 [*abbr. 11*])

$D_{i_8} = T_{e_2} + T_{d_1} + T_{i_{12}}$ (Event 2, Rescue Team 1, Patient 8 [*abbr. 12*])

$D_{i_9} = T_{e_2} + T_{d_2} + T_{i_{21}}$ (Event 2, Rescue Team 2, Patient 9 [*abbr. 21*])

$D_{i_{10}} = T_{e_2} + T_{d_2} + T_{i_{22}}$ (Event 2, Rescue Team 2, Patient 10 [*abbr. 22*])

$D_{i_{11}} = T_{e_2} + T_{d_3} + T_{i_{31}}$ (Event 2, Rescue Team 3, Patient 11 [*abbr. 31*])

$D_{i_{12}} = T_{e_2} + T_{d_3} + T_{i_{32}}$ (Event 2, Rescue Team 3, Patient 12 [*abbr. 32*])

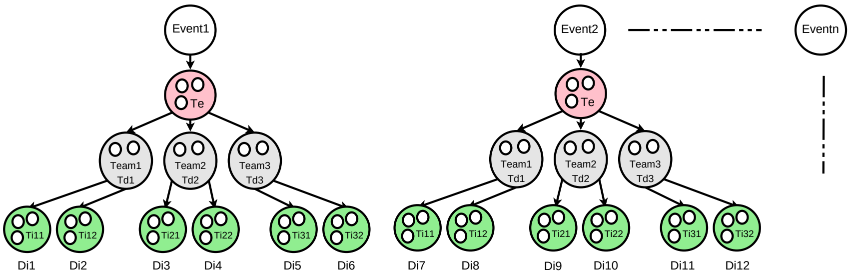

Figure 4: Multiple-Event Time Management in a prehospital Smart Emergency System.

5 DISCUSSIONS

As mentioned in the introduction of this paper, the presented model fits well as an interface between the recorded timing data and IoT-based emergency response devices/robots/vehicles/systems. Figure 5 highlights the multiple-event model for a smart emergency system.

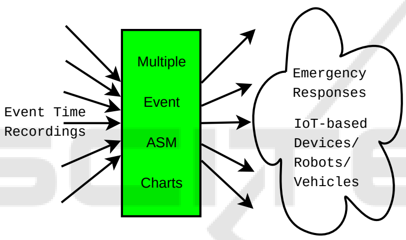

Figure 5: Multiple-Event ASM-based Model for a prehospital Smart Emergency System.

The timely recordings of a health-threatening event can be fed into the presented system interface either directly or through timing software[1]. The presented model consists of multiple-event ASM charts that can be integrated into the hardware of emergency response measures in order to deliver an effective IoT-based smart emergency system.

It is important to mention that in IoT-based healthcare systems, sensors are commonly used to detect health anomalies, and accordingly notify the healthcare officials about such anomalies. Such IoT-based sensors, which can be wearable devices, reduce the duration of detection and notification in a smart emergency system. However, IoT-based emergency response devices/robots/vehicles (e.g. (Samani and Zhu, 2016)) may automatically move for rescue based on the timing data provided by the presented model.

[1] For example: https://www.timelinemaker.com/

6 CONCLUSION

This paper presents an ASM-based model of a prehospital smart emergency system that can be an embedded interface solution to IoT-based environments. The model possesses inherent timely information leading to quick emergency responses in different stages of a health-threatening event. In addition, it can handle multiple events that may occur simultaneously, where multiple ASMs can be implemented to process timely information in parallel. Parallel ASMs improve prehospital smart emergency systems and subsequently minimize the mortality rate that may result from health-threatening events. This presentation of the proposed model provides a detailed timing analysis to show how prehospital emergency duration can be minimized to save lives and reduce the mortality rate. Embedded systems' developers can implement the model using hardware and software, at the purpose of achieving better prehospital smart emergency systems.

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