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Modelling alarm management workflow in healthcare according to IHE framework by coloured Petri Nets

Maria Pia Fanti [a,*], Stefano Mininel [b], Walter Ukovich [b], Federica Vatta [b]

[a] Dipartimento di Elettrotecnica ed Elettronica, Polytechnic of Bari, Bari, Italy
[b] Dipartimento di Elettrotecnica, Elettronica e Informatica, University of Trieste, Trieste, Italy

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ABSTRACT

Ensuring patient safety in medical device networks by managing alarms and related clinical data is a life-critical issue. The Integrating the Healthcare Enterprise (IHE) initiative emerged to discuss and solve the interoperability and integration problems among medical information systems, vendors and users in order to improve patient care and healthcare system dependability. This paper models and analyzes the IHE Alarm Communication Management by using the Unified Modelling Language and Coloured Timed Petri nets. Aiming at generality, the model does not refer to a specific healthcare context but it is based on a general scheme where the message transactions are integrated with the nurse responses. In order to show the potentialities of the model, a real case study is simulated and different scenarios with different levels of workload are analyzed. The results illustrate that the model is able to provide support for structured and comprehensive analysis of the healthcare system management.

1. Introduction

Many hospital enterprises are rapidly moving to extensive integration of both patient care process and information system, thanks to the advances in information technology and related fields. In addition, major medical device companies have designed patient monitoring systems that automatically reconfigure themselves for different hospital applications. Moreover, managing alarms of medical devices and related clinical data is a life-critical issue in order to avoid exposing patients to serious injuries (Gehlot and Sloane, 2006). Consequently, an emergent and challenging subject inherent to the healthcare system dependability is the management of the medical alarm devices integrated with the hospital workflow planning.

Integrating the Healthcare Enterprise (IHE) (IHE.net Home. Available at http://www.ihe.net/) is an initiative that has the goal of establishing a reliable integrated environment for medical devices and clinical information systems. Indeed, IHE identifies the key transactions required to automate processes, reduce errors and increase efficiency. The IHE is organized across a number of clinical and operational domains that produce a set of technical framework documents. In particular, the domain of the IHE Patient Care Device (IHE PCD) (IHE Patient Care Device Technical Committee, 2008) addresses the integration of medical devices with healthcare computer systems and intends to improve the flow of information between the point-of-care and the electronic healthcare record (Ettinger et al., 2009; Carr and Moore, 2003). Moreover, the IHE PCD technical framework is composed by a set of profiles that address specific integration scenarios including at least one regulated medical device. In particular, in the IHE PCD domain, the Alarm Communication Management (ACM) profile (IHE Patient Care Device Technical Committee, 2008; Booch et al., 2005) establishes interoperability between systems of different manufacturers, and results in a communication standard for alarm messages. It defines the communication of alarms from alarm source systems to alarm manager systems and from alarm manager systems to alarm archiver systems. Hence, ACM "is meant to improve clinical efficiency by using technology to deliver the right alarms, with the right priority, to the right individuals via devices and transactions with the right content" (IHE Patient Care Device Technical Committee, 2008).

The objective of this paper is a better understanding the IHE PCD ACM profile for more effective and integrated implementation. The related literature deals with the problem of analyzing and modelling the IHE scheduled workflow integration profile (Hussein and Winter, 2008) and testing the standards in e-health domain (Vega et al., 2010) in order to facilitate the adoption of the IHE concepts and to study the interoperability scenarios. In particular, Ettinger et al. (2009) developed an extensible open source toolkit based on the ACM profile and interfaced the patient monitoring equipments by means of suitable export interfaces. Moreover, some contributions deal with the workflow management (Nie et al., 2009; Dallien et al., 2008), and translate the IHE integration profile into Petri Net (PN) workflow models to bridge the gap between traditional applications and process-oriented healthcare solutions. Sloane and Gehlot (2005) use Coloured Timed Petri Nets (CTPNs) to model a medical device alarm management system. However, the model leads just to describe the system behaviour and does not accurately follow the corresponding ACM

* Corresponding author.
E-mail addresses: fanti@deemail.poliba.it, fantimp@tiscali.it (M.P. Fanti).

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profile. The aim of the paper is analyzing, modelling and simulating the healthcare information system related to the ACM profile integrated with the wireless medical device network and the heathcare operators. The modelling procedure follows two steps. First, the ACM profile is described and analyzed by means of the Unified Modelling Language (UML) (Miles and Hamilton, 2006), a graphic and textual modelling language intended to understand and describe systems from various viewpoints. Second, the behaviour of the ACM profile inside healthcare enterprises is modelled by regarding it as a Discrete Event System (DES), whose dynamics depends on the interaction of discrete events, such as the sending/reception of messages and the actions of the involved actors (e.g., the nurses). Among the available DES models, CTPNs (Jensen, 1992) are selected as a graphical and mathematical technique to describe concurrency, conflicts and synchronization. In particular, CTPNs are an enhancement of PNs in which the tokens have "colour" or types, and time is introduced to evaluate performances. Moreover, CTPNs are able to combine the strengths of PN with the strengths of a high-level programming language, and are suitable to model healthcare systems (Jørgensen et al., 2008). Indeed, the structure of the CTPN provides the primitives for process interaction, while the programming language provides the primitives for the definition of data types and the manipulations of data values. In this paper, the proposed CTPN describes in a unified modelling framework the heterogeneous system, comprising medical devices, information system and human resources. Hence, the paper describes the alarm management system exploiting the two main peculiarities of the CTPNs: the graphical characteristic of the CTPN, which enables the description of the system, easy to build and to verify; the mathematical and software translation of the CTPN, which allows simulating the system and evaluating the performances. In order to show the effectiveness of the presented modelling technique, a real case study is analyzed and simulated considering a simple IHE PCD ACM profile. The obtained results show how the CTPN model and the performance analysis help in the verification and validation of such a profile.

The paper is organized as follows. Section 2 illustrates the Alarm Communication Management profile, and Section 3 describes the corresponding CTPN representation. Moreover, Section 4 specifies the simulation experiments, and reports the simulation results. Finally, Section 5 discusses the conclusions.

2. The Alarm Communication Management profile in IHE PCD domain

This section describes the ACM profile devoted to the alarm dissemination between alarm source devices and systems, from the connector and within the communication services to the required abstract semantics, in a manner that enables multi-vendor multi-modality interoperation.

2.1. Alarm Communication Management profile description

The ACM profile supports the remote communication of point-of-care medical device alarm conditions and specifies the communication of alarm data, describing states and events significant for patient care, devices to alarm management systems. These alarms are of two types: (i) physiological, i.e. they represent the physiological state of the patient (such as a heart rate above or below a caregiver-specified safe range for the patient); (ii) technical, i.e. they reflect conditions in the patient care devices themselves that may require actions from caregivers (such as ECG leads of the patient).

In order to describe the ACM profile, it is necessary to single out the actors involved in the alarm management system and the messages exchanged among them. Here, the message flowing between the involved actors is described by the UML communication diagram that depicts the way in which the objects dynamically cooperate with each other. More precisely, in the UML communication diagrams the rectangles represent the various objects involved, the lines connecting the objects represent the relationships between them. Each message is depicted as an arrow that indicates the direction of the message. Moreover, each message is labelled by a number that indicates the sequence of interactions between the actors. Fig. 1 shows the UML communication diagram describing the main actors of the ACM profile and the relevant transactions among them (Health Level Seven, 2007). In particular, the ACM profile defines the following actors: the Alarm Reporter (AR) that represents the medical device, the Alarm Manager (AM) that is the actor that disseminates the messages, the Alarm Communicator (AC) that corresponds to the actor that communicates with the clinical staff, and the Alarm Archiver (AA) that archives and stores the messages. Moreover, the transactions exchanged between the described actors that are depicted in the UML communication diagram in Fig. 1, are the following:

The Alarm Reporter actor originates the alarm and sends it to the Alarm Manager actor with the Report Alarm transaction.
The Alarm Manager actor receives the alarm from the Alarm Reporter and analyzes it. If the alarm is physiological, then it dispatches to the Alarm Communicator (AC) actor the Disseminate Alarm transaction; if the alarm is technical then the

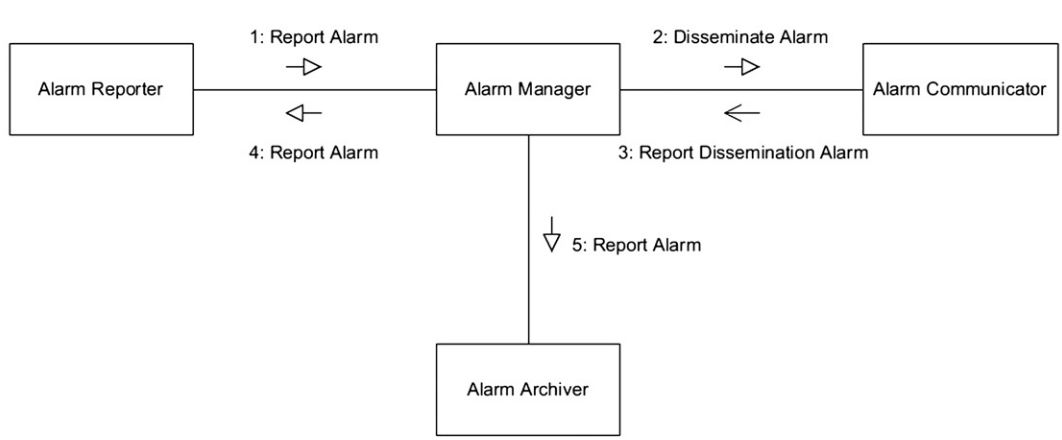

Fig. 1. UML communication diagram of the ACM profile: actors and transactions.