Ontology-Driven Monitoring of Patient's Vital Signs Enabling Personalized Medical Detection and Alert

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Abstract. A major challenge related to caring for patients with chronic conditions is the early detection of exacerbations of the disease that may be of great significance. The dedicated clinical personnel should be contacted immediately and possibly intervene in time before an acute state is reached, by changing medication, or any other interventions, in order to ensure patient safety. This paper presents an Ambient Intelligence (AmI) framework supporting real-time remote monitoring of patients diagnosed with congestive heart failure. The remote monitoring environment, enhanced with semantic technologies, provides a personalized, accurate and fully automated emergency alerting system that smoothly interacts with the personal physician, regardless his/her physical location in order to ensure in time intervention in case of an emergency. The proposed framework is able to change context at runtime in case new medical services are registered, new rules are defined, or in case of network overload and failure situations.

Keywords: Medical workflows, Ambient Intelligence, Semantic reasoning, Medical Ontologies, Medical Alarm, Quality of Service (QoS).

1 Introduction

During the past decade technology has gradually been moving to the concept of Ambient Intelligence (AmI) in which smart environments help inhabitants in everyday life. AmI supports pervasive diffusion of intelligence in the surrounding environment, through various wireless technologies (Zigbee[1], Bluetooth[2], RFID[3], WiFi[4]) and intelligent sensors. The first applications appearing in the clinical

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[1] http://www.zigbee.org/

[2] http://www.bluetooth.com/

[3] http://en.wikipedia.org/wiki/Radio-frequency_identification

[4] http://en.wikipedia.org/wiki/IEEE_802.11

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domain were mainly focused on addressing the need to better support remote patient monitoring (vital sign monitoring [1], soft copy radiological film review [2]) and provide condition specific diagnostics and treatment [3]. Such e-health applications and wireless medical devices can significantly improve quality of health care and promote evidence-based medicine. Later it became apparent the need to provide services able to interconnect all the fragmented available e-health systems and automation systems, in order to realize integrated platforms facilitating time-critical care in case of an emergency. In this direction our framework provides: i) personalized monitoring of chronic disease patients that is able to detect the patient's health status, ii) intelligent alerting of the dedicated clinician in case of an emergency, iii) dynamic adaptation of the full vital signs' monitoring environment in any available device located in close proximity to the clinician and iv) ontology-based modeling of the patient's and clinician's context and the available devices. To achieve such functionality the following device and technologies were available in our paradigm:

- Wireless or wearable medical devices and sensors acquiring patient's vital signs. In our reference implementation the supported measurements are: Blood Pressure[5] (BP), SpO_2[6], Heart Rate (HR), body weight[7] and 12-lead ECG monitoring[8].
- Indoor Localization System (ILS) [4] consisting of a network of sensors used as anchor points in order to specify the location of a person. Commonly used techniques involve RFID tags, triangulation algorithms based on WiFi signal (strength, angle, distance, attenuation), infrared and visible light communication and ultrasound waves. Depending on the cost, the required precision and the use case-specific parameters, various solutions or combinations can be applied.
- Monitoring application recording the aforementioned bio signals and hosting risk assessment algorithms to enable the alerting process. A full description of this application as applied in a clinical environment is described in [5].
- Ontology-driven application intelligence capable of reasoning on the patient data and available (medical) devices. The applied medical and device ontologies define a formal representation of knowledge by a set of key domain concepts and the relationships between those concepts enabling reuse of the medical knowledge and device interoperability.

In order to illustrate the AmI framework in real use, a specific scenario related to Congestive Heart Failure (CHF) is proposed in the next section.

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[5] A&D UA-767PBT Blood Pressure Monitor acquiring BP (systolic, diastolic and mean arterial) measurements and HR, transmitted via Bluetooth.

[6] Nonin Avant 4000 Digital Pulse Oximeter providing real time measurements of HR and SpO_2, transmitting via Bluetooth.

[7] A&D UC-321PBT Weight scale measuring the person's weight, transmitting via Bluetooth.

[8] Welch Allyn Cardio Perfect 12 lead ECG Recorder transmitting the recorded ECG via fiber optic cable.

2 Vital Signs Monitoring and Alert Detection Scenario

Our dedicated framework receives real-time patient data and processes them to detect possible deviations from normal values (Figure 1). When a threshold is exceeded (step 1) the dedicated clinician is localized and alerted (step 2, 3) and redirected to a better display (step 4) in order to overview in detail the vital signs (step 5).

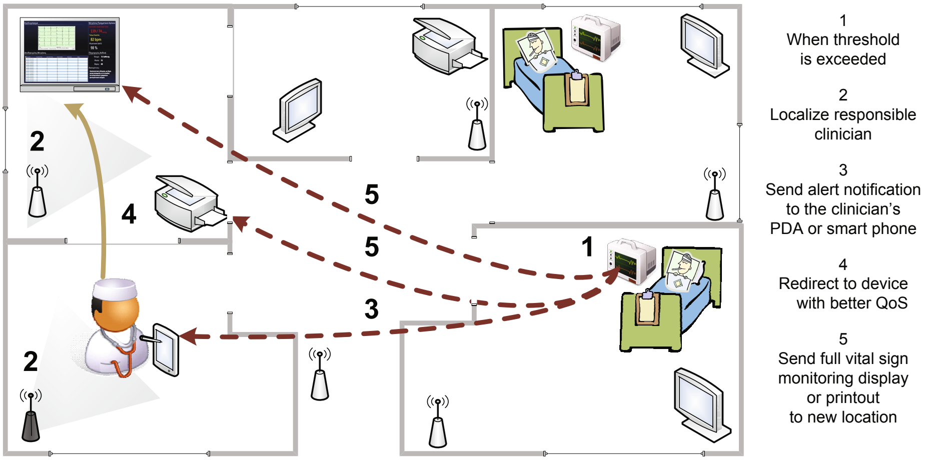


Fig. 1. Localization and notification of the responsible clinician during an emergency

The parameters and default thresholds are illustrated in Table 1. In case of exceeded thresholds, medical personnel are localized and contacted presenting ad-hoc information on the patient's condition on any device within the clinician's reach. In order to further tailor the system to the patient's profile and assist physicians in selecting people who are predisposed by coronary disease, hypertension, or valvular heart disease; we build a CHF related risk profile based on the risk appraisal function proposed in [6] that is based on the Framingham Heart Study [7] (486 heart failure cases during 38 years of follow-up).

The predictors used are based on **Age**, **Coronary heart disease** and **Valve disease status** provided by the patient Electronic Health Record (EHR), as well as on **HR**, on **blood pressure** and on **Body Mass Index** (BMI) provided by the pulse oximeter, the blood pressure monitor and the weight scale respectively. The calculated risk probability may be used to alter the default threshold values (higher risk probability add more constraint on the physiological patterns presented in Table 1).

3 Ontology-Driven Alert Detection

A requirement for an AmI environment monitoring patients with chronic conditions is interoperability between heterogeneous devices and technologies. These

Table 1. Alert detection parameters and corresponding thresholds

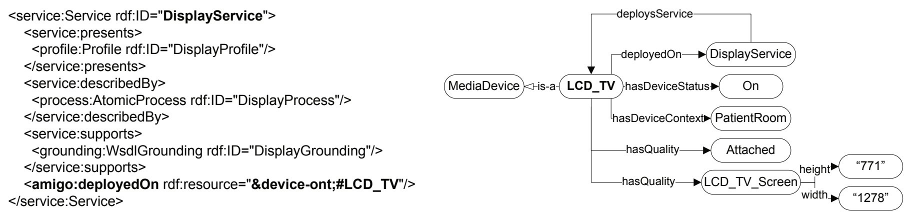
Measurement	Monitoring Device	Detection Threshold
low SpO_2	Pulse Oximeter	$SpO_2 < 90\%$
bradycardia	Pulse Oximeter	HR < 40 bpm
tachycardia	Pulse Oximeter	HR > 150bpm
HR change	Pulse Oximeter	$\lvert \Delta$ HR / 5min$\rvert > 19\%$
HR stability	Pulse Oximeter	max HR variability past 4 readings > 10%
BP change	BP Monitor	systolic or diastolic change > ±11%

devices and the services running on them should be automatically discovered and executed based on semantically-defined features. Additionally an intelligent behavior should emerge through the notion of user (patient or clinician) context allowing for a smart and personalized combination of the available resources.

3.1 Device and Service Ontology

In the presented AmI framework, the available (medical) services are enriched with semantic annotations using the latest version of OWL-S 1.2 [8]. Instead of defining their inputs and outputs using XML Schema types much like WSDL they are expressed by ontological concepts in OWL. For the definition of the service preconditions and effects OWL-S supports the use of SWRL (Semantic Web Rule Language) expressions and built-ins (SWRLB) such as comparisons (equal, less than, greater than, etc), math functions (add, subtract, multiply, divide, etc) [9]. SWRL expressions are used for coding procedural relation in the form of rules. This formal service specification, allows the use of existing description logic reasoners such as Pellet [10] for the execution of data transformations.

The OWL-S service description is extended with the Amigo [11] device ontology. It defines deployment properties between a device and its running services. Amigo provides support for communication protocols such as Universal Plug and Play (UPnP), Service Location Protocol (SLP), Java RMI and Simple Object Access Protocol (SOAP), description of device and user context and QoS information. Using the Amigo ontology one can define a Display service, presented in Figure 2(a) consisting of the standard OWL-S Profile, Process and WSDL Grounding, and additionally specifying a device instance it is deployed on (e.g. LCD TV screen). This explicit deployment specification enables runtime selection of a service depending on the device QoS parameters. The example in Figure 2(b) presents the modeling of a Display service deployed on a LCD TV screen, an instance of a "MediaDevice" concept, having properties such as location, screen parameters, mobility features and device status. This results in the definition of semantically equivalent display services running on different devices. The dynamic selection of a specific service will depend on the semantically defined device parameters.



```
<service:Service rdf:ID="DisplayService">
  <service:presents>
    <profile:Profile rdf:ID="DisplayProfile"/>
  </service:presents>
  <service:describedBy>
    <process:AtomicProcess rdf:ID="DisplayProcess"/>
  </service:describedBy>
  <service:supports>
    <grounding:WsdlGrounding rdf:ID="DisplayGrounding"/>
  </service:supports>
  <amigo:deployedOn rdf:resource="&device-ont;#LCD_TV"/>
</service:Service>
```

(a) Device addition to OWL-S Service description.

(b) Device properties

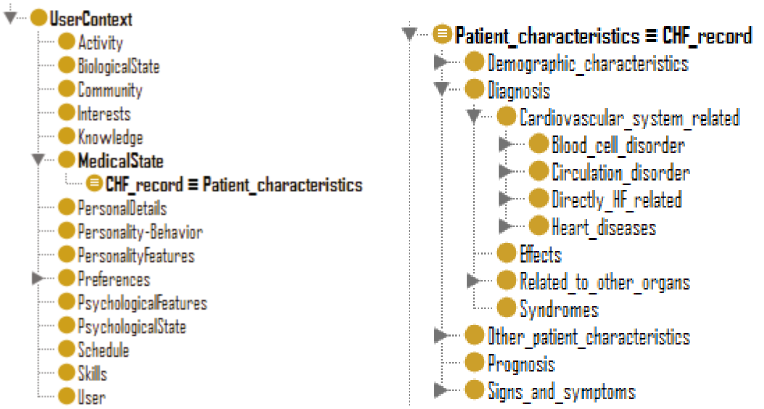
Fig. 2. Service deployment on context-rich devices

3.2 Medical Patient State Ontology

The Amigo ontology not only supports the definition of a device context but also of a user context. The user context presented in Figure 3(a) includes among others the user's activity, schedule, and personal details. In order to model the chronic heart conditions of a specific patient it is extended with a medical state concept consisting of a CHF concept (CHF_record) defined as an equivalent concept of the HF ontology [12,13] (Figure 3(b)). This ontology presents a detailed taxonomic overview of the heart failure domain with around 200 classes describing HF related concepts. Examples are "Cardiac_hypertrophy", "Blood_pressure_signs", "Heart_murmurs". The five basic super-classes are:

- **HF_concept:** describes HF terminology, including the risks for CHF, medical synonyms, and types of classification. The classification taxonomy is extended in order to support the previously mentioned Framingham Heart Study risk factors.
- **Patient_characteristic:** contains clinical data in the patient's HF medical record such as demographical characteristics, possible diagnoses, possible signs and symptoms, prognosis and other characteristics. This concept is linked to the Amigo ontology through sub classing of a user's medical state.
- **Testing:** represents knowledge regarding physical examinations and tests performed in medical institutions. Each test relevant to HF has properties that denote the measurements for that test and also which disorders it can detect.
- **Treatment:** consists of medical procedures used in the healing process, including medications, devices, invasive and non-invasive procedures, and recommendations regarding HF.
- **Patient:** reserved for factual knowledge about particular patients.

The new ontology models the patient's context including his medical state and focuses on the CHF scenario. Using these concepts, rules are defined for monitoring the patient condition, suggesting patient classification according to his/her risk profile and specific alerts are sent in case of deteriorated vital signs (e.g. elevated HR).



(a) User Context (b) Patient Record for congestive heart failure

Fig. 3. Ontological definition of a patient's medical state according to a specific model for the heart failure disease

4 The AmI Monitoring Framework

The main building blocks of the AmI environment for monitoring patients with chronic heart conditions are presented in Figure 4. It is designed based on the principles of Service-Oriented Architectures (SOAs) [14], wherein all medical components and devices are implemented as Web services. The Web service technology enables reuse of services for gathering medical data values from patient monitoring devices resulting in a component-based system. Depending on defined or automatically calculated thresholds the acquired patient measurements are sent to the clinician's tablet PC, printer or a nearby TV screen [15]. When needed, medical services are also invoked on request to query for overviews of historical decision outputs and results.

The AmI components subscribe for specific events to the **Execution Environment** managing the processing steps of the monitoring and alerting system. Repository of the available AmI services and their semantic OWL-S

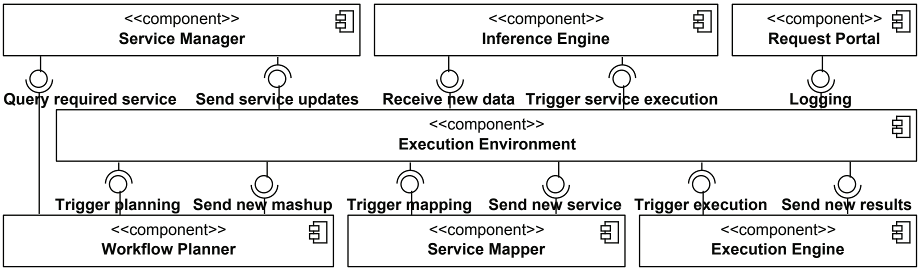


Fig. 4. AmI patient monitoring and emergency detection framework architecture

descriptions is the **Service Manager**. It enables automatic querying for service interfaces or devices offering specific QoS (defined using the extension on the Amigo ontology). In the presented AmI framework a service is viewed as a state-based rule; "`IF Service-Preconditions THEN Service-Effects`". These service rules and additional user-defined rules stating the default medical thresholds are uploaded to the **Inference Engine** which uses Pellet reasoning on new patient measurements to evaluate rules. Whenever a service precondition or a user-defined rule is satisfied by the available data, the **Inference Engine** triggers the execution of that service. Services scheduled for execution are passed on to the **Workflow Planner** which decides if additional data is required such as patient data from medical services and responsible clinician contact details. Combining these services a medical workflow is constructed using HTN planning described in [16]. This workflow is translated into an executable composite process by the **Service Mapper** through a specification of the data and control bindings between the services. For each semantic service description an actual executable service instance is selected depending on the device capabilities it is deployed on and the clinician's context (e.g. location). Usually a notification is sent to his personal tablet PC. Through device comparison of QoS properties like screen height and width extra services are triggered to summarize the patient data for a small screen and supply information on device locations with better resolution. Following is the actual execution by the **Execution Engine** handling the invocation workflow of the services. The service results are added to the **Inference Engine** enabling a dynamic system inferring new knowledge at runtime. The **Request Portal** provides an overview of the constructed medical workflow.

5 Conclusion

This paper presents the development of an ambient intelligence framework supporting real-time monitoring of patients diagnosed with congestive heart failure. Services monitoring vital patient signs are transformed into SWRL rules evaluated by a Pellet-based Inference Engine. Planning algorithms are implemented that automatically assemble medical workflows out of existing semantically enriched services. Dynamic adaptation of the constructed medical workflows take into account the clinician's location and succeed in remotely displaying the full vital sign monitoring application in the device of his/her choice, in order to ensure in time intervention in case of an emergency. The proposed framework is able to change context at runtime in case new services are registered, new rules are defined, or failure/overload of the network, through dynamic reconfiguration and personalization of the constructed workflows.

Future work includes the extension of the AmI framework with dynamic distributed deployment making optimal use of the available resources for the execution of the alerting services during an emergency.

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