# SAPHIRE: A Multi-Agent System for Remote Healthcare Monitoring through Computerized Clinical Guidelines

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**Abstract.** Due to increasing percentage of graying population and patients with chronic diseases, the world is facing serious problems for serving high quality healthcare services to citizens at a reasonable costs. In this paper, we are providing a Clininical Desicion Support system for remote monitoring of patients at their homes, and at the hospital to decrease the load of medical practitioners and also healthcare costs. As the expert knowledge required to build the clinical decision support system, Clinical Guidelines are exploited. Examining the reasons of failure for adoption of clinical guidelines by healthcare institutes, we have realized that necessary measures should be taken in order to establish a semantic interoperability environment to be able to communicate with various heteregenous clinical systems. In this paper these requirements are detailed and a semantic infrastructure to enable easy deployment and execution of clinical guidelines in heteregenous healtcare enviroments is presented. Due to the nature of the problem which necessitates having many autonomous entities dealing with heteregenous distributed resources, we have built the system as a Multi Agent System. The architecture described in this paper is realized within the scope of IST-27074 SAPHIRE project.

## 1. Introduction

The World is facing problems to provide high quality healthcare services at a reasonable cost to the citizens due to the increasing percentage of graying population. According to a study performed by United Nations, by 2050, 22 percent of

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the World's population, nearly 2 billion people, will be 60 and older. With the demographic change, the prevalence of chronic conditions such as chronic respiratory and vessel diseases increases: the percentage of elderly at 60s and older having at least one chronic disease is more than 60 [1]. The solution to decrease both the cost of healthcare services and also the load of medical practitioners requires a dramatic change in the way future healthcare services are provided. The expected necessary changes are: moving from reactive to preventive medicine, concentrating on the long term care rather than only acute care, citizen centered care rather than hospital centered care, including remote care delivery mechanisms where the citizen is taking a bigger role in his/her treatment and lifestyle management. All of these necessitate technologies for long term monitoring of the patients both in hospital and home settings.

Enabling underlying infrastructures such as wireless medical sensor devices, wearable medical systems integrating sensors on body-worn platforms like wrist-worn devices or biomedical clothes are offering pervasive solutions for continuous health status monitoring through non-invasive biomedical, biochemical and physical measurements. Remote monitoring systems typically collect these patient readings and then transmit them to a remote server for storage and later examination by healthcare professionals. Once available on the server, the readings can be used in numerous ways by home health agencies, by clinicians, by physicians, and by informal care providers. However remote healthcare monitoring systems will be exploited to their full potential when the analysis is also performed automatically through clinical decision support systems fed by expert knowledge. Clinical practice guidelines constitutes the most suitable source of information for building such clinical decision support systems.

Clinical practice guidelines are the systematically developed statements designed to assist practitioners to make decisions about appropriate medical problems. They aim to reduce inter-practice variations and cost of medical services, improve quality of care and standardize clinical procedures [2]. In order to be able to share clinical guidelines and manage their enforcement through computerized systems, a number of machine processable models of Clinical Guidelines have been proposed such as GLIF [3], ASBRU [4], ARDEN [5] and EON [6]. Based on these machine processable guideline definitions, a number of clinical decision support systems have been built such as GLEE [7], GLARE [8] and DeGel [9].

Despite the benefits of clinical guidelines, and also although we have such machine processable models and clinical decision support systems for execution them, it has been a well accepted fact that wide adoption computerized clinical practice guidelines has yet to be achieved even within a single healthcare institute. This is because of the difficulty of integration of clinical decision support systems with the already existing clinical workflow systems run by healthcare institutes: for this the clinical decision support system needs to communicate with various heterogeneous clinical applications run by the healthcare institute [10, 11]. Especially in the case of long term and remote monitoring of the patients, the clinical decision support systems need to communicate with many different information sources:

medical devices, several electronic healthcare record systems, and the decisions need to affect the processes held at disparate care providers such as homecare, emergency centers, primary and secondary care, and rehabilitation centers. Hence we definitely need robust clinical guideline execution systems that can cope with semantic and technical integration problems with disparate healthcare information systems.

In this paper, the SAPHIRE project will be introduced which provides a Multi-Agent system for the monitoring of chronic diseases both at hospital and also in home environments based on a semantic infrastructure. The system is capable of deploying and executing clinical guidelines in a care environment including many disparate care providers having heterogeneous information systems. In Section 2, the challenges and requirements of deploying and executing a clinical guideline execution infrastructure for remote monitoring of patients in a heterogeneous care environment will be detailed. In Section 3, the SAPHIRE Multi-Agent System that addresses these challenges through an enabling semantic interoperability environment will be introduced. Finally Section 4 will conclude the paper, discussing the current status and future challenges.

## 2. The requirements for seamless execution of Clinical Guidelines for long term healthcare monitoring

In order to guarantee successful execution of clinical decision support systems for long term monitoring of patients based on clinical practice guidelines, the integration, more importantly interoperability, with the following external interfaces should be assured:

- *Accessing vital signs of the patient:* In order to be able to monitor the patient's current condition, the clinical decision support systems need to access the vital signs of the patient measured by wireless medical sensors and body-worn platforms. Currently there are many biomedical sensors devices available, and active research is going on for body worn platforms initial products of which will be soon in the market. The clinical decision support systems should be able to communicate with heterogeneous medical devices supplied by various different vendors. We have two interoperability problems to access the vital signs measured by these devices: the first one is the technical interoperability problem to access the vital signs physically: there may be different protocols implemented by different medical device vendors. In SAPHIRE architecture we are addressing the technical level interoperability problem by exposing the sensor data through Web Services. The sensor data is gathered through Bluetooth from wireless sensor devices to a gateway computer where they are exposed as Web services. By exposing the sensor data as Web services, a platform independent way of accessing the vital signs measured by sensor devices is achieved. The second interoperability challenge that should be addressed is content level interoperability problem: After accessing the sensor data through Web services, the content received should be processable and interpretable by the receiving application, the clinical decision support system in our case. However, the data coming from the wireless medical sensors are either in proprietary format (for example, for electrocardiogram data, Philips XML ECG Data Format) or when it conforms to a standard, this still does not solve the interoperability problem since there are very many standards (again for electrocardiogram data, the available standards include: SCP-ECG [12], US Food and Drug Administration FDA/HL7 Annotated ECG [13], I-Med [14] and ecgML[15]). There is also a very important interoperability initiative for the interoperability of the data coming from medical devices: the IEEE 11073 Standards Family[16] which aims to enable functional and semantic ad-hoc interoperability. For this purpose, the IEEE 11073 proposes an Object-oriented modeling of function and application area, the "Domain Information Model" (DIM). Through the DIM it is possible to define and represent devices, functionalities, measurement data, calibrations, alert information and so on. On top of the DIM, it provides standardized codes for naming all information elements in the DIM such as medical devices and device systems, units of measurements through the "Nomenclature" and "Data Dictionary". IEEE 11073 assumes that all device vendors to adopt this DIM to represent sensor data to achieve interoperability. However for the time being the vendors still using proprietary formats or different standards can not be ignored. For this purpose, in our architecture we provide a translation wizard, through which the translation of proprietary XML schemas of sensor data to the IEEE 11073 format can be easily defined graphically enabling the user to define Javascripts taking the pieces of input XSD schema. This translation definition is used to transform the data instances automatically to one another. In this way it is possible to have all the sensor data in IEEE 11073 format in SAPHIRE Gateway computer to be exposed as Web services.

- *Accessing Electronic Healthcare Records of the Patient:* The gathered vital signs of the patient can only be assessed correctly when consolidated with the Electronic Healthcare Records (EHRs) of the patient. The evaluation of the vital signs should be "personalized" for each patient, based on their past illnesses, active problems, family histories, allergies and adverse reactions. In addition to this, the clinical decision support system executing clinical guidelines needs to know the previous medical history of the patient to follow the correct branch for the medication or operation recommendations to be presented to the medical staff: for example the first line medication to be applied to a patient who may be suffering from myocardial infarction varies based on his/her medical history: it is not appropriate to recommend a B-blocker if the patient previously suffered from bronchial spasm or asthma. To be able assess these, the clinical guideline execution environment needs to access the Electronic Healthcare Records of the Patient where ever they are. However there is a challenge to be addressed here: Patient medical records that the clinical decision support system need to process are usually physically dispersed in disparate medical institutions which usually do not interoperate with each other. First of all the Clinical Decision support system needs to discover these records, and then needs to seamlessly access the records to process them. One of the prominent initiatives for sharing EHRs is the Integrating Healthcare Enterprise (IHE). IHE, through the Cross Enterprise Document Sharing Integration Profile (XDS) [17], enables a number of healthcare delivery organizations to share clinical records. This profile has received considerable attention and appeared in the National eHealth System blueprints of Canada, USA, Italy, Norway and France.

In the IHE XDS Profile, healthcare enterprises that agree to work together for clinical document sharing are called a "Clinical Affinity Domain". Such institutes agree on a common set of policies such as how the patients are identified, the access is controlled, and the common set of coding terms to represent the metadata of the documents.

In each affinity domain there are a number of "Document Repositories"; the healthcare institutes store the medical documents of the patients to these repositories in a transparent, secure, reliable and persistent way. There is a "Document Registry" which is responsible for storing information about those documents so that the documents of interest for the care of a patient may be easily found, selected and retrieved irrespective of the repository where they are actually stored. The document repositories register the documents along with a set of metadata to the Document Registry. Whenever a "DocumentConsumer" wishes to locate a specific document of a patient, the "Query Document" transaction is issued along with the specified query criteria, and as a response a list of document entries that contain metadata found to meet the specified criteria is returned including the locations and identifier of each corresponding document in one or more Document Repositories. Using these document identifiers and the Document Repository URI's, the "Retrieve Document" transaction is issued to get the document content.

The SAPHIRE multi-agent system that facilitates the execution of the clinical decision support system uses this IHE Profile to locate and access the records of the patients which will be detailed in Section 3.

The Electronic Healthcare Records accessed should be machine processable so that the content can be interpreted to retrieve the necessary piece of the EHR required by the clinical guideline definition. For this purpose in SAPHIRE architecture, the EHR documents are represented as the HL7 Clinical Document Architecture (CDA) [18] documents. The HL7 CDA is a document markup standard that specifies the structure and semantics of "clinical documents" for the purpose of exchange. CDA documents are encoded in Extensible Markup Language (XML) and they derive their machine processable meaning from the HL7 Reference Information Model (RIM) [19] and use the HL7 Version 3 Data Types. In the SAPHIRE architecture, both the "Sections" and "Document Entries" are annotated with coded terms of medical terminologies and ontologies such as LOINC [20], SNOMED [21] and ICD-10 [22] so that the clinical guideline execution environment can process the information contained in the EHR of the patient. However it should be noted that, in the clinical guideline definition the clinical information requested may have been represented through a code in a different medical terminology from the one that has been used in the CDA document, in this case, the "Ontology Agent" of SAPHIRE multi agent system is contacted to handle the mediation between different coding standards.

- *Accessing the Clinical Workflow systems executed at Healthcare Institutes:* While the clinical decision support system is executing the Clinical Guideline Definition, it is needed to interact with several modules of the clinical workflow executed at the healthcare institutions. For example, if the clinical decision support system recommends to prescribe a B-Blocker to a patient, this medication recommendation should be reflected to the underlying clinical workflow, otherwise the clinical decision support system and the clinical workflow run in parallel without any interaction with each other, the activities are not synchronized with each other. This hampers the use of clinical decision support systems to their full potential. For this kind of interactions like medication, procedure or lab orders, there needs to be an interface provided by the underlying hospital information system executing the clinical workflow. However most of the hospital information systems are proprietary, which makes the deployment of clinical decision support systems to healthcare institutes difficult. Integration with each of such hospital information system is costly; there needs to be a mechanism that enables interoperability for accessing these proprietary systems to avoid manual integration efforts. In SAPHIRE, we are proposing to solve this problem by exposing the functionalities provided by Healthcare Institutions as Web Services, and publishing these Web services to Service registries by annotating them with ontologies reflecting their functionality. This will allow us to automatically deploying the clinical decision support systems executing clinical guidelines automatically. Web services have already started to be adopted by the Healthcare Industry as a solution to technical interoperability problem. The Dutch national infrastructure for healthcare messaging is implemented by wrapping HL7v3 messages as Web services [23].

## 3. The SAPHIRE Multi Agent System

The SAPHIRE Clinical Decision Support System that is responsible for deploying and executing Clinical Guidelines is a multi-agent system composed of a number of collaborating agents. An overview of the subcomponents and their interaction is depicted in Figure 1. The system is implemented as a multiagent system, since as a result of conceptual design phase we have realized that in order to deploy and execute the clinical guidelines in a heterogeneous distributed environment, there

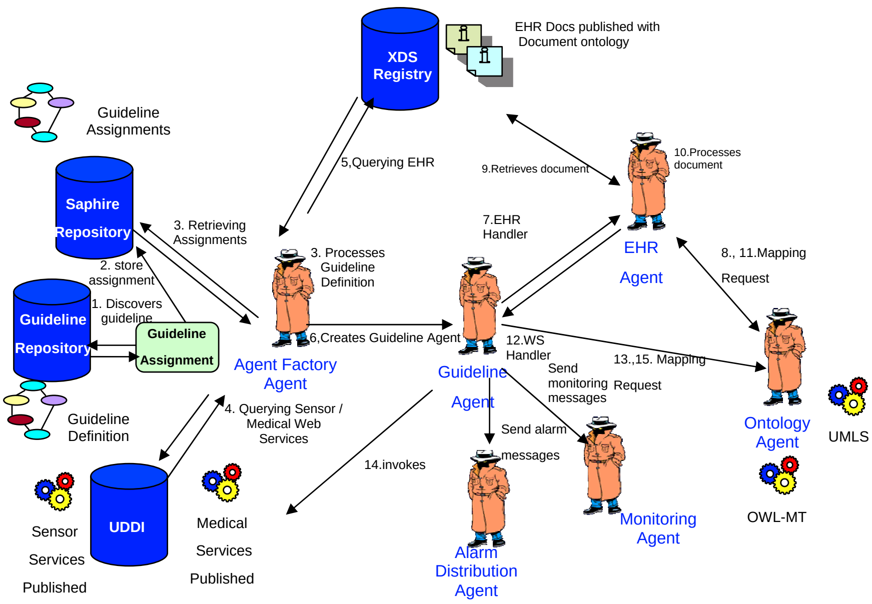


FIGURE 1. The SAPHIRE Multi Agent System

should be a number of autonomous components that should be communicating with each other in a reactive manner, and some of these components should be instantiated and eliminated dynamically based on the demand.

The roles of each SAPHIRE Agent can be introduced as follows:

- *Agent Factory Agent*: The Agent Factory Agent is mainly responsible for specializing the Guideline definition to a patient, and creating the Guideline Agent which will execute the clinical guideline. It discovers the real implementations of the medical services exposing hospital information system functionalities and sensor services and the document identifiers of the EHR documents of the patients, so that the guideline definition becomes ready to be executed.
- *EHR Agent*: In the SAPHIRE architecture the EHR agent functions as the gateway to access and extract clinical data from the Electronic Healthcare records of the patient. EHR Agent is modelled as a separate agent, to abstract the access to EHR from other agents. Currently in the SAPHIRE architecture the main mechanism for sharing EHR documents is IHE XDS Registry/Repository architecture. The EHR agent is capable of communicating with IHE XDS Registry/Repository to retrieve the EHR documents.
- *Ontology Agent*: The SAPHIRE architecture is capable of reconciliation of semantic interoperability problems while accessing the resources of healthcare

institutes. In the SAPHIRE in the guideline definition, patient data references are modelled in a reference information model based on HL7 RIM. It is possible that the medical Web services, the sensor data, and the EHR documents use different reference information models, and clinical terminologies. Through Ontology Agent this semantic interoperability problem is solved.

- *Guideline Agent*: The guideline agent is the main entity which executes the Clinical practice guidelines. The Guideline agent processes the guideline definition specialized to a patient and executes the activities specified in the guideline definition. It can be thought as the enactment engine for the clinical guideline. The guideline agent exploits several modular handlers to achieve this responsibility.
- *Monitoring Agent*: While the guideline is executed, the current status of the guideline execution is sent to a specific agent which we call Monitoring Agent. Monitoring Agent provides an interface to the Clinical Practitioners to visualize the execution of the guideline.
- *Alarm Distribution Agent*: While the guideline is executed, several alarms, notifications, reminders may need to be issued to medical practitioners, and when necessary to the patient relatives. In such cases the alarm message and the role to whom the message should be delivered is informed to an agent, the Alarm Distribution Agent, which is specifically designated to distribute these messages to the necessary recipients in the most efficient and reliable way.

For implementing the SAPHIRE Multi Agent system we have utilized the JADE [24] agent development platform. In the following sections the functionalities of the SAPHIRE Agents will be detailed.

### 3.1. EHR Agent

As presented in section 2, accessing the Electronic Healthcare Records of the patient is an indispensable requirement for automatic remote monitoring of the patient. However the EHR's of a patient may be stored separately in each healthcare institute s/he has been previously hospitalized. In SAPHIRE Architecture, the healthcare institutes that cooperate for the care of a patient are grouped as Clinical Affinity domains. These clinical affinity domains may have agreed on different platforms for sharing the EHRs of the patient that are not interoperable with each other. This is in fact a real life situation: in U.K as the national health infrastructure, a central architecture called SPINE [25] will be used for sharing medical summaries of patients, while in Canada, an IHE-XDS based infrastructure is being built for the same purpose [26]. To abstract the access to the EHR from the Clinical Guideline Execution Environment, we have created a dedicated agent, the EHR agent for each such affinity domain. EHR agent can be thought as a gateway for locating and accessing EHRs of the patients. Each EHR agent is specialized in the platform agreed in that affinity domain for sharing EHRs. When a request for discovering and requesting an EHR document is received by an EHR agent, the EHR agent both tries to locate the EHR document within its affinity domain, through the methodology agreed by the clinical affinity domain such as IHE-XDS, and also forwards the request to the EHR agents of the other clinical affinity domains. In this way, the EHR documents will be available to the requesting entity, although heterogeneous systems are used by different affinity domains. In our architecture, we have implemented EHR agents accessing the IHE-XDS EHR Registry/Repositories: When a specific EHR of a specific patient is saught, an EHR Discovery message is sent to the EHR Agent. In this message, the patient identifier is presented and the document type metadata is specified with "LOINC Document Type Codes" such as "11450-4" for "Active Problems". Using this metadata, and the patient identifier, a "QueryDocument" transaction is issued to the XDS Registry, and as a response a set of Document Identifiers pointing to document stored in EHR Repositories is presented. These document identifiers are used to access the document content from the Repositories by issuing a "RetrieveDocument" transaction.

Apart from locating and retrieving EHR documents, EHR agents also serve another important feature: retrieving a specific piece of information from the EHR content. The EHR content standard agreed by each clinical affinity domain may be different, however the EHR agent of that domain, is capable of processing the document format agreed and extract the requested piece of information in the format requested by the Clinical guideline execution environment. As presented in section 2, in our architecture, we are using HL7 CDA documents as EHR documents, and in our implementation, we have implemented an EHR agent that is capable of processing the CDA document, locate the requested piece of information among the CDA Entries, and present it to the requesting entity.

In the EHR access request sent to the EHR Agent, the semantics of the piece of information requested is also specified with coded terms. For example, the Clinical Guideline Execution Environment is in need of discovering whether the patient has previously experienced "asthma". In the request sent to the EHR agent, besides the document type code for "Past illnesses", the coded term representing "asthma" is also specified for example as "C0004096" in UMLS medical terminology. In the CDA document all the entries are also annotated with coded terms, however another code from a different terminology may have been used for identifying the same entry in the CDA document which could be the "J45" term from ICD-10 terminology. To solve this interoperability problem, the EHR agent consults to the Ontology agent, and receives an answer to its translation request. In this way although different medical terminologies may have been used, the requested part of the EHR can be extracted from the whole EHR document.

### 3.2. Ontology Agent

The Ontology Agent in SAPHIRE Architecture is responsible for handling the semantic mediation of the clinical content used in SAPHIRE Architecture. It is used for the following purposes as presented in Figure 2:

- *Mapping the parameters of Medical Web Services*: In the SAPHIRE Architecture, the guideline execution environment uses a reference information model

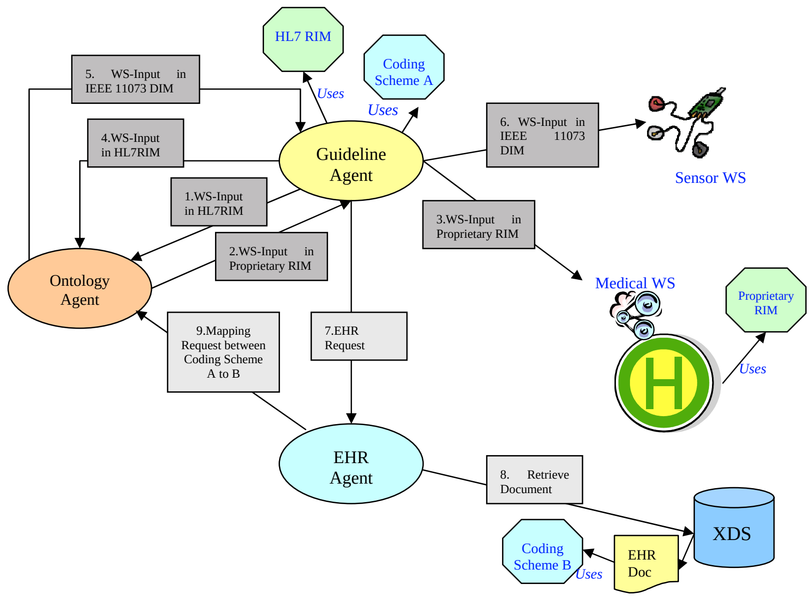


FIGURE 2. The SAPHIRE Ontology Agent

based on HL7 RIM subset to represent the clinical information. However, it is a fact that several other standards or even propriety formats may be used by the healthcare institutes to represent clinical information. The guideline execution environment needs to communicate with the hospital information systems to reflect the results of guideline execution. For example, the guideline execution can result with a proposal of prescription of a medication to the patient; in this case this information may need to be stored to the hospital information system to affect the clinical workflow. In SAPHIRE architecture, these kinds of interactions are handled through the Web services exposed by the healthcare institutes. However it is natural that the parameters of these Web services are conforming to the messaging and content standards used within the hospital, not to the one used in the guideline execution environment. Whenever the Guideline Agent needs to invoke a Medical Web Service, it consults with the Ontology Agent and the input parameters are automatically mediated to the messaging and content standards used by the hospital. The same mechanism is used for mapping the output parameters.

- *Mapping the parameters of Sensor Web Services*: In the SAPHIRE Architecture, the guideline execution environment represents the sensor data to be used in guideline execution in the same reference information model based on HL7 RIM. Currently in our architecture the sensor data will be exposed

***An example translation request***

```
(request
  :sender
   (agent-identifier
     :name client-agent@foo.com
     :addresses (sequence iiop://foo.com/acc))
  :receiver (set
   (agent-identifier
     :name ontology-agent@foo.com
     :addresses (sequence iiop://foo.com/acc)))
  :protocol FIPA-Request
  :language FIPA-SL2
  :ontology FIPA-Ontol-Service-Ontology
  :content
   (action
     (agent-identifier
       :name ontology-agent@foo.co
       :addresses (sequence iiop://foo.com/acc))
   (translate (C0262926))
     (translation-description
       :from UMLSDocTypeOntology
       :to LOINCDocTypeOntology)))
  :reply-with translation-query-1123234)
```

***An example response to a translation request***

```
(inform
  :sender
   (agent-identifier
     :name ontology-agent@foo.com
     :addresses (sequence iiop://foo.com/acc))
  :receiver (set
   (agent-identifier
     :name client-agent@foo.com
     :addresses (sequence iiop://foo.com/acc)))
  :language FIPA-SL2
  :ontology (set FIPA-Ontol-Service-Ontology)
  :content
   (= (iota ?i
     (result
       (action
         (agent-identifier
           :name ontology-agent@foo.com
           :addresses (sequence iiop://foo.com/acc))
      (translation-description
        :from UMLSDocTypeOntology
        :to LOINCDocTypeOntology))) ?i))
     (11348-0))
  :in-reply-to translation-query-1123234)
```

FIGURE 3. An example translation request and response

as Web services which represent the data in IEEE 11073 DIM. Whenever a data is received form a Sensor Web Service, the Guideline Agent consults with the Ontology Agent to mediate the sensor data to the reference information model used in the guideline execution environment.

- *Mapping the content of the Electronic Healthcare Records of the Patient*: In the SAPHIRE architecture the Electronic Healthcare Records of the patients are represented as HL7 CDA documents. In HL7 CDA, the document sections and entities can be coded with coded terms from different coding schemes. In SAPHIRE, in the guideline definition model the EHR data can also be annotated with concepts from ontologies or coding schemes. Whenever different coding scheme standards are used, the Ontology Agent is consulted for mediation. Since the Guideline Agent cooperates with the EHR Agent whenever an EHR content is necessary, the mediation request to Ontology Agent is sent by the EHR Agent.

The Ontology Agent is compliant with the FIPA Ontology Service Specifications [27]. According to FIPA Specification an Ontology Agent is an agent that provides access to one or more ontology servers and which provide ontology services to an agent community. The Ontology Agent (OA) is responsible for the one or some of these services:

- maintain (for example, register with the DF, upload, download, and modify) a set of public ontologies,
- translate expressions between different ontologies and/or different content languages,
- respond to query for relationships between terms or between ontologies,

The FIPA Specification deals with a standard way to serve the ontology services; it does not mandate any mechanism on how to map the ontologies to one another. As well as all the other agents, the OA registers its service with the Directory Facilitator (DF) and it also registers the list of maintained ontologies and their translation capabilities in order to allow agents to query the DF for the specific OA that manages a specific ontology. Being compliant with the FIPA Ontology Service Specification necessitates the Ontology Agent to be able to accept and respond to the ontology service requests in FIPA-Ontol-Service-Ontology ontology. An example translation request and response is presented in Figure 3.

As presented the FIPA Ontology Service Specification does not deal with how the mapping is facilitated. In the SAPHIRE Architecture, the mapping is facilitated through three different mediation mechanisms (Figure 2):

- *Mapping the parameters of Medical Web Services*: In one of our previous projects, Artemis [28], we have developed an OWL Ontology Mapping Tool, the OWLmt [29], to mediate the input and output parameters of medical Web services between different standards. The SAPHIRE Ontology Agent handles such mapping requests through the OWLmt tool. The OWLmt tool provides a graphical interface to define the mapping patterns between OWL ontologies in different structures but with an overlapping content. This mapping definition is used to automatically translate ontology instances to one another. In SAPHIRE, the schemas of Web service messages, and the schema of the Reference Information Model used by the clinical guideline execution environment are lifted to metamodel level and and represented as OWL ontologies. Then through the OWLmt GUI, the mapping relationships between them is defined graphically once, which will be used by the OWLmt Mapping engine to mediate the Web service parameters to the reference information model understood by the clinical guideline execution environment. For the details of the OWLmt tool, please refer to [29], where detailed examples of mapping definitions from medical domain are presented.
- *Mapping the terminologies used in Clinical Document Content*: The SAPHIRE Ontology Agent handles such requests through a Web service exposing the functionalities of the UMLS Knowledge Source Server [30] . The UMLS Metathesaurus contains information about biomedical concepts and terms

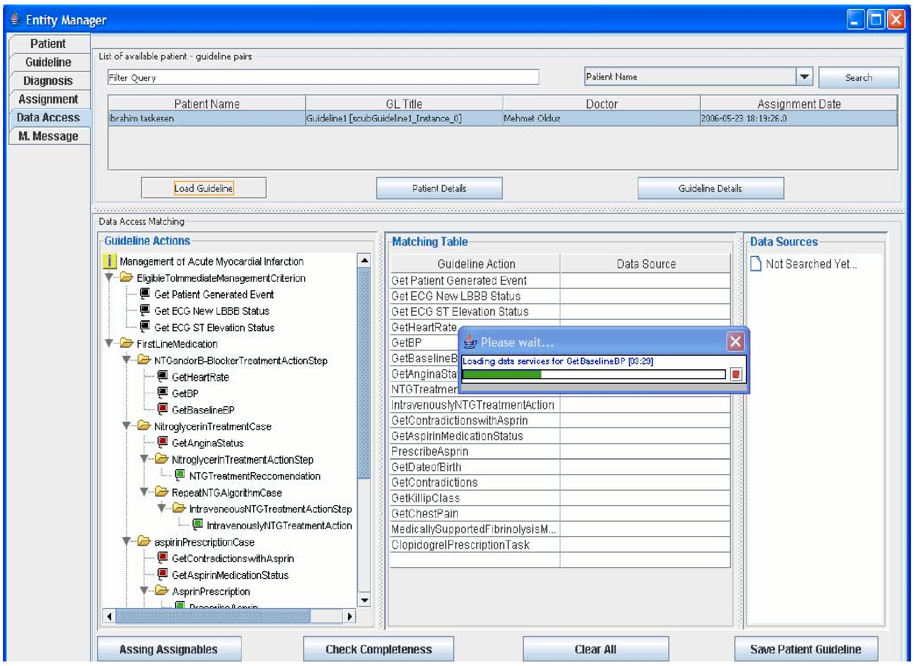


FIGURE 4. The SAPHIRE Agent Factory GUI

from many controlled vocabularies and classifications used in patient records, administrative health data, bibliographic and full-text databases, and expert system. These are referred to as the “source vocabularies” of the Metathesaurus. The Metathesaurus reflects and preserves the meanings, concept names, and relationships from its source vocabularies. The UMLS Knowledge Sources are also downloadable as databases in UMLS Site. In SAPHIRE architecture, we have implemented a Web service that queries the local UMLS database, for finding the synonyms of clinical terms. synonym terms in ICD10, LOINC and SNOMED CT if there are any.

- *Mapping the parameters of Sensor Web Services*: As presented in Section 2 the Sensor data is exposed as Web services in IEEE 11073 DIM. However this information in DIM, should be translated to HL7 RIM which is used by the clinical guideline execution environment. The IEEE 11073 Standards family names this level as “Observation Reporting Interface”, and provides guidelines to map the IEEE 11073 DIM to the HL7 observation reporting messages, segments, and fields. The SAPHIRE Ontology agent implements these guidelines to handle this mediation.

### 3.3. Agent Factory Agent

In the SAPHIRE Architecture the agent that is responsible for leading the deploying a generic clinical guideline definition to a specific patient in a healthcare institution is the Agent Factory Agent.

In SAPHIRE, we have selected GLIF (Guide Line Interchange Format) [3] as the computer interpretable model of clinical guidelines. However GLIF was originally developed as a standard representation model for sharing guidelines among different healthcare institutes, rather than automatically deploying clinical guidelines to a healthcare institute. For example, when clinical information is needed to be retrieved, in the original GLIF, only "EHR" or "Doctor" can be represented as the source of clinical information. It is apparent that with this amount of information it is not possible to use it as an executable model of clinical guidelines. This necessity as the "requirement for an implementable representation" is also specified in GLIF's latest specification as a future work.

Within the scope of SAPHIRE project, we have extended the original GLIF model, and semantically annotated the external interfaces of the guideline execution environment with EHR systems, Medical sensor devices and Healthcare Information Systems so that the required resources such as EHR documents can be dynamically discovered in the deployment phase. We have extended the model so that:

- the functionality of the medical procedures to be interacted can be specified through ontologies.
- both the type of the EHR document sought, and also the type of the piece of information looked for in the EHR document can be specified through ontologies or medical terminologies.
- the kind of vital signs can be specified through a coded term in reference to a terminology identifying medical measurements such as IEEE 11073 Nomenclature.

The details of this extension can be found in [31, 32].

The Agent Factory Agent processes the clinical guideline definitions represented in our extended model, and based on the semantic annotations of the external resources, discovers the instances of the specified resources that are relevant for our specific patient. This process can be summarized as follows:

- In SAPHIRE architecture, the medical Web services exposing functionalities of healthcare information systems, and also the sensor Web services exposing the sensor data retrieved from wireless medical sensor devices are published to a UDDI registry by annotating them with their functionality semantics. Whenever the Agent Factory encounters a reference to a medical procedure, it locates the medical procedures from UDDI service registries by their functionality which has been specified in the extended GLIF model.
- Whenever the Agent Factory encounters a reference to a clinical data of patient to be retrieved from an EHR document, it sends a message to the EHR agent presenting the Document type, and Entry type semantics presented in

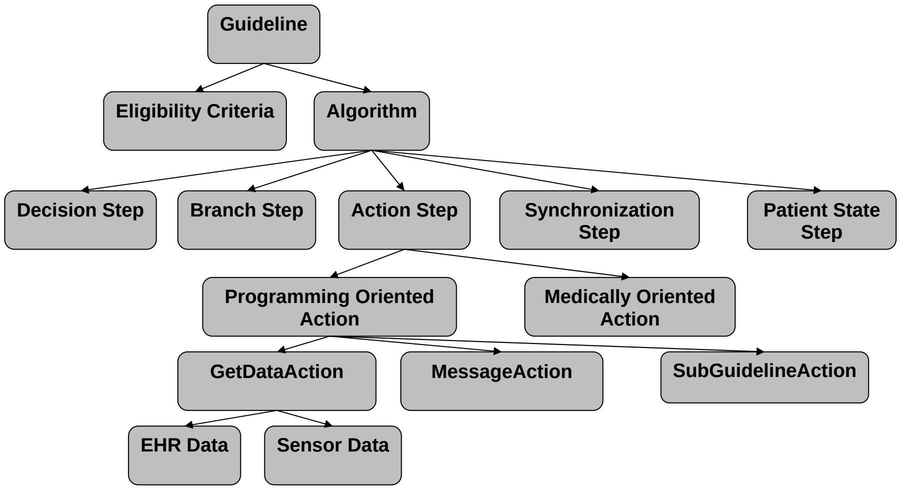


FIGURE 5. The SAPHIRE Guideline Agent Handlers

the extended GLIF model. As a response a set of document identifiers are received pointing to relevant EHR documents.

In addition to that, in the extended GLIF model, we have also reserved slots for storing the pointers to the discovered resources, for example, document identifiers in EHR repositories, the WSDL and OWL-S files of Web services. As a result of the deployment phase briefly presented, the agent factory specializes the generic guideline definition to a patient by filling in these slots.

Whenever the clinical guideline is wished to be executed for remote monitoring of a specific patient, the Agent Factory Agent instantiates a dedicated Guideline Agent for a specific guideline patient pair. In addition to this, the Agent Factory Agent informs the Monitoring Agent, about this instantiation, so that the execution of the remote monitoring process can be traced by clinical practitioners.

### 3.4. Guideline Agent

Guideline agent is the leading agent that coordinates the execution of the clinical guideline definition for remote monitoring of the patients. SAPHIRE Guideline agent is capable of processing any guideline definition represented in the extended GLIF model, and execute the guideline in cooperation with the other entities of SAPHIRE Multi Agent System. As presented in Figure 5, the guideline definition is composed of a number of building blocks, for each building block we have implemented modular handlers. The SAPHIRE Guideline Agent behavior is implemented to process the extended guideline definition and instantiate these modular handlers as follows:

- The main body of a clinical guideline is represented in the "Algorithm" building block. "Patient State steps" are not executable, can be though as labels for current situation of the patient. The "Branch and Synchronization Steps" coordinate the execution of serial or parallel execution of algorithm branches. The "Decision Steps" coordinate the control flow of the guideline, by evaluating the expressions on patient state. In SAPHIRE, the expressions are represented as Java Scripts using the content of the EHR documents and vital signs received from sensors as parameters.
- The "Medically Oriented Actions" represent the medical Web services in the extended GLIF definition. The guideline agent extracts the WSDL of the Web service from the guideline definition specialized to a patient by the Agent Factory Agent. The Guideline agent prepares the input parameters in HL7 RIM, since GLIF uses this RIM for representing clinical data. While the Web services are discovered from the UDDI registry by the Agent Factory, the OWL-S files of the Web services are also retrieved and saved to the specialized guideline definition. Using this OWL-S file, the Guideline agent checks the semantics of the input/out parameters, and sends a translation request to the Ontology Agent to translate the input messages from the HL7 RIM to the message schema specified in the OWL-S file. The same procedure is repeated when the output is received from the Web service.
- The "Get Data Actions" can be used to represent either references to EHR document or to vital signs of the patient to be retrieved from wireless medical sensor devices through Sensor Web services. The Sensor Web services are also invoked as the Medical Web service, by contacting with the Ontology Agent to mediate the input and output parameters.

  Whenever a reference to a clinical information presented in an EHR document is encountered by the Guideline Agent in the guideline definition, the Guideline Agent sends a request to the EHR agent, with the document identifiers previously filled by the Agent Factory Agent, and also with the semantic annotation of the clinical data to be extracted from the EHR document. As presented, the EHR agent parses the document, consults to Ontology agent when necessary to reconciliate the coded terms one another, and as a response sends the requested content in HL7 RIM to the Guideline Agent. The Guideline Agent stores all of these clinical data, sensor data to a global variable pool, so that other handlers such as "Decision Step Handler" can make use of them when necessary.
- The "Message Actions" are used to generate alarm messages within the clinical guideline execution. When the Guideline Agent encounters a "Message Action" during clinical guideline execution; it immediately constructs an alarm message by combining information coming through guideline definition and agent properties. Alarm message, healthcare role id to whom the message is to be delivered and alarm urgency parameters are retrieved from guideline definition whereas patient and guideline ids are retrieved from agent properties. The constructed alarm messages are transmitted to "Alarm Distribution

Agent", which actuates the delivery. The transmission is performed through JADE [24] messaging and ontology facilities.

### 3.5. Alarm Distribution Agent

Alarm Distribution Agent is responsible from accurate and punctual delivery of alarm messages to the healthcare users. It triggers the distribution of the alarms when it receives such a request from the Guideline Agent.

Alarm Distribution Agent employs a role based delivery mechanism, in which the real responsible healthcare users for a patient-guideline pair are determined based to the role id indicated by the alarm message. There are four pre-determined role ids which are administrator, doctor, nurse and patient relative. Through a web based interface, the healthcare users can subscribe to receive alarm messages related with a specific patient guideline pair. Alarm messages are delivered to the users through three different mediums: SMS, GoogleTalk Instant Messaging and secure e-mail. The users can customize their preferences for receiving alarm messages in different urgencies (medium type, number of deliveries, acknowledgement requirement, routing option etc.) through a web based user interface. User preferences are stored as JESS [33] rules. These rules are executed in delivery time and the delivery terms are determined.

Acknowledgement facility is a confirmation mechanism in order to ensure reliable delivery of the alarm messages. With this option, users are required to confirm that they have received the alarm messages. For e-mail and Instant Messaging, the acknowledgment method is simply replying to the message; SMS acknowledgment is realized through delivery confirmation message. In case that the message is not acknowledged, it is re-sent to the user for a number of times determined based on user preferences; if the message is still unacknowledged; it is routed to another healthcare user which is specified by the healthcare user.

### 3.6. Monitoring Agent

Monitoring Agent presents a graphical user interface to the healthcare users for clinical guidelines. Through the Monitoring Agent Interface, healthcare users can start/stop and monitor the execution of clinical guidelines by interacting with the guideline agent. In addition to these, guideline agent can consult to the healthcare professionals' decisions through this component.

Guideline execution is monitored on a user friendly interface which is composed of three parts. The main part of the interface depicts the flowchart of the clinical guideline model, whereas the others are for the message sequence and legend of the flowchart. Guideline execution can be traced on the flowchart model. The status of the guideline steps (committed/ongoing/ not visited) are identified with different colors. User can click on the steps to get detailed information about the step. In the detailed information screen, user can view the tasks, retrieved patient data (sensor, EHR etc.) and the invoked medical services within these tasks. In case that, the medical experts decision is needed, Monitoring Agent displays a pop-up window for consulting. In this way, input is provided for Guideline Agent.

The communication between Monitoring Agent and Guideline Agent is realized via JADE[24] messages. The messages are implemented in JADE ontologies in order to structure a well defined message format for monitoring and consulting. The communication between agents is based on a publish-subscribe mechanism in which multiple monitoring agents can be subscribed to one single Guideline Agent.

Apart from these, an important outcome of the Monitoring Agent is the visual model that it provides for clinical guidelines. This visual flow-chart model can be utilized as an educative medium in training healthcare professionals.

## 4. Conclusion

The architecture described in this paper is realized within the scope of IST-27074 SAPHIRE project. The prototype implementation is achieved using JADE Agent Platform.

The SAPHIRE has two pilot applications: in the hospital pilot we address the bedside monitoring of subacute phase of the patients suffering from myocardial infarction; in the homecare scenario we address the homecare monitoring of the rehabilitation of the cardiovascular patients undergone a revascularization therapy. A more detailed discussion of SAPHIRE pilot applications can be found in [34]. Through these pilot applications, the system aims to increase adherence to the guidelines, hence provide standardization to care processes, to reduce costs of care with optimal benefit for the patient and doctor, to reduce human error in hospital events/complications and finally to provide a feedback system for medical staff in training.

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