

TOWARDS AN AGENT-ORIENTED ARCHITECTURE OF THE DIGITAL HEALTHCARE ECOSYSTEM

Andrei VASILĂTEANU¹, Luca Dan ȘERBĂNAȚI²

Această lucrare abordează problematica cadrului aplicațiilor de e-sănătate. Pornind de la o trecere în revistă a stării actuale a cercetării, standardelor și a proiectelor derulate în e-sanatate, se descrie un nou model conceptual, bazat pe paradigma ecosistemelor digitale și se propune o implementare bazată pe sisteme multi-agent.

Trecerea de la modelul conceptual al ecosistemului digital și de la arhitecturile și aplicațiile existente către un model bazat pe sisteme multi agenți o denumim agentificare și prezintarea etapelor ei face de asemenea obiectul de studiu al acestei lucrări.

The purpose of this paper is to provide a framework for the e-health application of the future. Starting from a state-of-the-art in e-health research, standards and projects, a new conceptual model based on the digital ecosystem paradigm and a multi agent system implementation is proposed.

We call agentification the transition from the conceptual model of the digital ecosystem and the existing architectures and applications towards a multi agent based model. Presenting the transition stages also constitutes the objective of this paper.

Keywords: e-health, digital ecosystems, multi-agent systems

1. Introduction

The purpose of this paper is to present a conceptual model of an innovative e-health system aimed towards supporting a continuum of care for chronically ill patients and to offer new opportunities to the stakeholders in the health system by introducing an open framework where health services can be published and discovered. Based on a thorough analysis of current e-health systems and practices we propose a solution based on the digital ecosystems paradigm, implemented with multi-agent systems (MAS).

The paper starts by presenting the state-of-the-art in e-health and in the approached domains, such as digital ecosystems and multi agent systems,

¹ Eng., Faculty of Engineering in Foreign Languages, University POLITEHNICA of Bucharest, Romania, e-mail: andrei.vasilateanu@upb.ro.

² Prof., Faculty of Engineering in Foreign Languages, University POLITEHNICA of Bucharest, Romania, Senior Researcher, National Research Council, Institute of Biomedical Technologies, Italy

continues with introducing a conceptual model for the health state and the digital ecosystem, the architecture of the system and agent characterization and ends with the current implementation status.

Numerous studies prompted the need for a greater role played by information technology in healthcare, its adoption transcending from the academic domain to the policy decision factors, both national and international. However, even if investments have been made, and programs started, the impact has not yet achieved its full potential, and more than one initiative has resulted in costly failures. We can associate these poor results to the problems usually encountered by large and complex software projects to which we must add the special difficulties found in the healthcare domain.

As mentioned, the medical knowledge alone that needs to be modeled prior to implementation is of vast extent and of a dynamic nature. Apart from the medical knowledge itself, modeling must take into consideration the full complexity of the healthcare system seen in its context where business processes are influenced by profound socio-economical and legal clauses, in fact processes defined by and influencing the society. Failure to analyze all these implications leads, in our point of view, to unsustainable projects which achieve only in compromising the trust in the effects of applying ITC in the medical field on a large scale. [1]

To understand and model such a system we need to apply different paradigms, able to capture a more realistic view, bridging the gap between the model and the system that needs modeling. It requires further major leaps both in the capabilities of ICTs and in the formal expression of socio-economic relations.

In the past two decades, much of the growth in health expenditures has been attributable to chronic conditions in the context of global population ageing. Future health reform should address changed health needs through care coordination and support for “patient empowerment” [2][3][4][5]. It is clear that efficiency and effectiveness of the health system and healthcare management of aged population become prime issues in the attempt of mobilizing the full potential of all people of all ages. The solution requires a shift of paradigm in healthcare towards patient-centric care provided by multidisciplinary teams in different settings along the continuum of a disease.

Healthcare is and has been a field of interest for the use of software agents. A software agent is a piece of software that acts autonomously in an environment to achieve its design objectives. A Multiple-Agent System (MAS) is a system composed of several software agents collectively capable of reaching goals unachievable by an individual agent or a monolithic system.

The agent-based paradigm is a natural way of representing many recurrently occurring situations in medical environments such as: absence of a central control, bounded or insufficient resources of a caregiver, and knowledge

and data distribution. Research projects have targeted specific use-cases of healthcare, such as workflow-oriented care plan monitoring or the establishment of agent-based virtual healthcare organizations around a patient. [6][7] Also, recent research in agent development methodology has stressed the need for collaborative environments such as e-health to focus also on organization- and artifact-based agent environment.[8]

The digital ecosystem approach transposes the ecosystem metaphor to the digital world reproducing some of the mechanisms of natural ecosystems. Digital Business Ecosystem (DBE) was designed to enable SMEs to create, integrate and provide services more efficiently and more effectively. It is a self-organizing digital infrastructure aimed at creating a digital environment for networked organizations that supports the cooperation, the knowledge sharing, the development of open and adaptive technologies and evolutionary business models. As a definition for digital ecosystem we will consider the DEBII (Digital Ecosystem and Business Intelligence Institute) definition: “an open, loosely coupled, domain clustered, demand-driven, self-organizing and agent-based environment within each species is proactive and responsive for its own benefit and profit”.

2. Modeling the health state

We need a unified view on the healthcare process and on the definition of the health state of the patient. The concepts and relations we define will be used as a reference model inside our envisioned digital healthcare ecosystem and the relation between them is presented in Fig. 1.[9]

By “health state” we define the reflection in our digital world of the “real” situation of the health of the patient. Here we must go through a number of abstractions to represent such a concept.[10] In the ontology of concepts [11] we have a separation between concepts seen as mental representations and concepts seen as abstract objects, which exist even in the absence of the views upon them. For us accurately modeling and representing of the health state of a patient is an ideal: we can never have a perfect matching between the “real” situation of the health of the patient and the digitally represented health state. However we can get tend to fill the gap by multiplying the observations. Such is the case of the diagnostic investigation where our represented health state is not an accurate enough match of the real situation of the health of the patient and we need additional observations to close the gap. Each new observation will change our representation of the health state so the patient’s health state will be in a permanent evolution, where old snapshots of the state are not discarded but archived.

The health state manifests itself to a stakeholder (caregiver or patient) in a partially observable way. We define “health condition” as the perceived part of the health state available to the stakeholder and manifested by symptoms, laboratory analyses and any other objective or subjective observation.

We name “health issue” a general medical problem such as asthma. Usually the patient will take notice of her/his modified health state, manifested in a health condition and will seek medical assistance. By analyzing the symptoms and/or performing additional analysis the healthcare provider will classify the condition in a health issue, by diagnosing. We must take into consideration that this classification may be wrong, partial or temporary and the identified health issues can be related one to another. The classification of the information in the health state into health issues is important because it is the trigger for starting the healthcare process related to that health issue. Using an evidence-based approach, the healthcare provider derives her/his plan of care from a clinical guideline which contains the approved and updated set of activities and rules of conduct applying to that health issue.

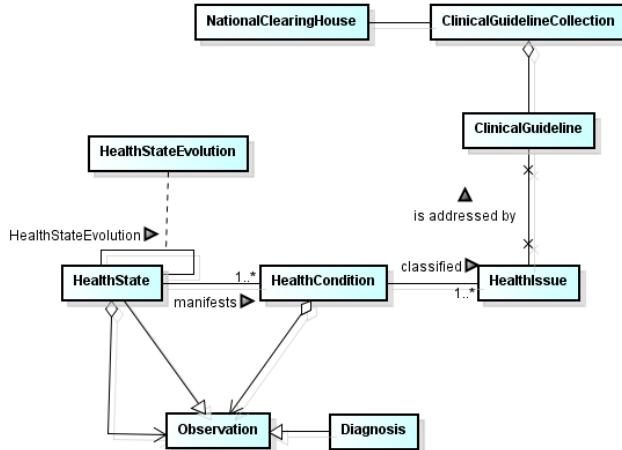


Fig. 1. Health state model

3. Virtual healthcare record

The Virtual HealthCare Record (VHCR) is the flagship in our envisioned digital health ecosystem. VHCR is a provider of electronic services supporting healthcare processes. It holds data, but is not a simple repository. Data is extracted from medical documents generated by various sources in a finer grained model than the document-based model permits.

VHCR's purpose is to maintain a unified, documented, coherent and consistent view on the clinical current status and history of the patient by integrating healthcare events generated throughout the whole life of the patient by different entities. The clinical documents that originate information in the VHCR are generated by the healthcare applications of the healthcare providers like general practitioners or specialists in the form of prescriptions, procedures and referrals organized into care plans, from laboratories in the form of blood tests or x-ray images or from medical devices like intelligent measurement devices for blood pressure or glicemy which can send the results wirelessly to a proxy. These documents are digitally signed by an authorized healthcare provider before being integrated within VHCR. Once the data has been integrated, and a "snapshot" of the patient clinical status is available, VHCR becomes a complex e-service provider, generating and providing customized views on this integrated status to the stakeholders involved in the healthcare process and responding to complex queries.

4. Digital healthcare ecosystem

A natural life ecosystem is defined as a biological community of interacting organisms plus their physical environment. The digital ecosystem approach integrates and uses the concepts of a given natural domain to the digital world, reproducing or interpreting some of the mechanisms of natural ecosystems. It is a self-organizing digital infrastructure aimed at creating a digital environment for networked organizations that supports the cooperation, the knowledge sharing, the development of open and adaptive technologies and evolutionary business models.

A digital ecosystem can be seen as a foundation framework, a viable and functional environment offering the technical infrastructure, regulations and existing relations on which other digital ecosystems can evolve.[12]

Digital ecosystems can reuse the available, shared infrastructure and also reuse common concepts, or share business definitions.[13]

A digital ecosystem, in analogy with a natural one, is composed of a digital environment and of digital species. The environment provides the necessary infrastructure, a common support environment and a generic basic infrastructure which includes basic services components, generic integrated solutions and infrastructure components. It includes the mechanisms for the composition, the evolution and the migration of the digital species among the different habitats.

The digital species are the autonomous, proactive and adaptive entities that populate it. Digital species are of a heterogeneous nature; in fact their diversity is what makes the digital ecosystem viable. Digital species interact one with each

other in long term, or ad-hoc ways, forming virtual partnerships and organizations, called digital communities. The organizations themselves are represented as adaptive entities in the digital ecosystem, interacting with other organizations and with the environment.

While in other systems the system components exchange matter or energy, in a digital ecosystem digital species are interacting through information flows. Information is any fact or idea expressed in a natural or formal language, digitalized and transported in the DE and processed by humans or computers. The information flow is what keeps the digital species “alive” and also dictates their evolution.

With the last concepts we can refine the definition of DE as “the dynamic and synergetic complex of Digital Communities consisting of interconnected, interrelated and interdependent Digital Species situated in a Digital Environment, that interact as a functional unit and are linked together through actions, information and transaction flows.” [14]

In analyzing the structure and the entities that populate a digital ecosystem, we must start on how our digital ecosystem reflects the ecosystem on which it is based, for example how a digital healthcare ecosystem is a reflection of the healthcare ecosystem. To that end we must study the “virtualization” of the real world in a digital world, how the business processes in the real world are understood, supported and implemented in the digital landscape.

A business is an organization designed to accomplish a certain objective, the mission of the organization. The business objective is achieved by the execution of business processes, composed of activities. The activities involve one or more stakeholders with their actions, which use different instruments and are carried out according to a set of business rules. The stakeholders are represented in the digital ecosystem as avatars of the stakeholders, virtual entities, able to interact in the digital environment but aiming towards realizing the objective of the represented stakeholder. In fact this “digitalization” is a very complex process in which we must decide what defines the identity and concerns (purposes, interests, desires, etc.) of a stakeholder in order to formalize them in a computable way. Recently researches have also stressed the necessity to represent even the moods of the corresponding entity such as feelings, concerns and objectives. [15]

The business organizations in the real world must also be transposed into their corresponding digital counterpart, digital communities. By analyzing our organization we want to extract the set of roles and the relationships between them, as these roles will be enacted by the avatars. In this case the avatar has a dual behavior – to represent the stakeholder concerns and to enact its role in the digital community. During its existence an avatar may play different roles while representing the same identity.

The instruments used by the stakeholder to achieve his goals are also represented as digital species which can evolve, become extinct or recombine in new compositions, offering new services. Such a digital species can be a software service which can be orchestrated with other services to provide new values.

Business rules must be made computable so they appear in the digital ecosystem as formalized business rules, expressed in a descriptive or imperative formal language.

We would like to apply the DE paradigm in healthcare having the patient at the center of our concerns. By modeling and implementing a digital healthcare ecosystem (DHE) we can expose the underlying business processes, allow new operators to enter the market, increase the semantic and organizational interoperability in this new digital landscape, in the end raising the quality and quantity of the available services to the patient.

In our envisioned DHE the digital species will be the representations of the stakeholders in the virtual world, together with all the interrelated, interconnected medical devices and clinical software applications such as clinical decision systems, electronic medical records, imaging software, billing software etc.

Digital species (DS) representing stakeholders need to act corresponding to the stakeholder needs and objectives, generally concerns. For that they have to assume a proactive role, using the environment resources and collaborating with other DSs to achieve their intended goals.

We model our avatars so that they can reflect the stakeholder concerns that are relevant from the healthcare point of view, thus a patient avatar will rather contain information related to the health state of the patient than his business or political agenda.

The environment offers the necessary technical infrastructure but also the norms, regulations, business process definitions, resources such as ontologies to the involved parties. The purpose of the environment is to allow the transfer of information (interoperability) from one DS to another. The healthcare digital environment is a highly dynamic one but also a restrictive one, norms for information transfer and security must be addressed with extreme care.

The real world is reflected in the DHE in the activities, knowledge, goals and organization of the digital species as seen in Fig 2.

Activities in the ecosystem are triggered by a certain situation in the environment of the agent. At their completion the activities have modified this environment. Such a situation in our case, a MedicalAct, can be a condition found in the health of the patient or a lack of knowledge of the health state. An activity in the ecosystem is transmitted in the digital ecosystem as an event or data flow, through the stakeholder avatars. This in turn will change the knowledge of the real world, as reflected in the digital ecosystem and will favor some activities to be executed internally, by the digital ecosystem agents.

This means that activities inside the digital ecosystem are indirectly and partially determined by actions in the real world.

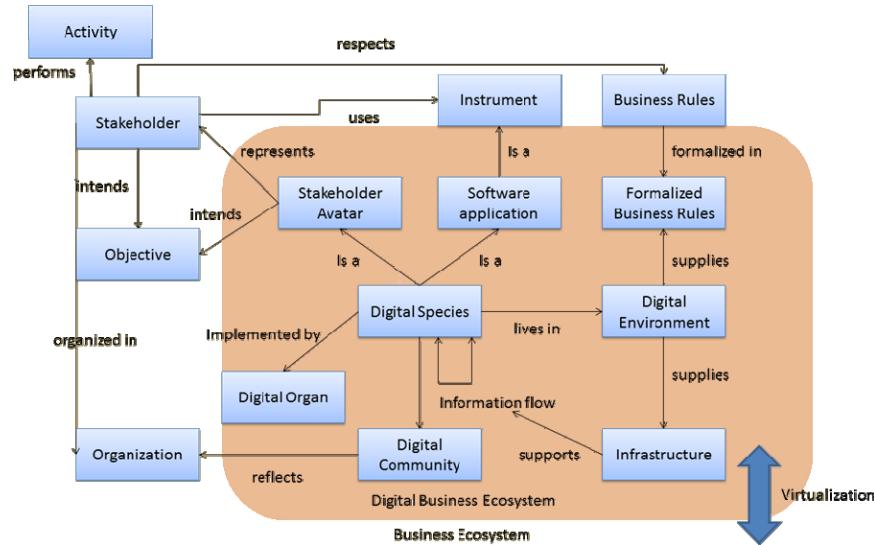


Fig. 2. Virtualization of a business ecosystem

Clinical events (observable changes in the health state of the patient) arrive as an information flow inside the digital ecosystem and can change the state of the patient avatar. A need in the real world is transformed into a care goal in the DHE. Reacting to this change in the environment, avatars representing different healthcare providers may participate to an ad-hoc multidisciplinary team, its structure and objectives generated by the process of solving that care goal.

The digital healthcare ecosystem is influenced by the healthcare ecosystem and it its turn influences the healthcare ecosystem by informational exchanges. The virtual organization created with that particular objective must be reflected in the real world. The team member avatars notify their owners of their new duties and corroborating their feedback with their agenda, negotiate between themselves for an agreed activity workflow. This cooperation is similar to a virtual enterprise in respect to the lifecycle: creation, operation, evolution and dissolution. However while for virtual enterprise the objective is to implement new, profitable supply chains, the metrics for virtual health organizations are the quality of health services reflected in the health state of the patient.

The structure of the team as well as the overall care process are influenced by other concepts in the real world exerting themselves as pressures on the DHE, appearing as formal restrictions in the digital world. Regulations, privacy laws, financial considerations all influence the DHE which must adapt to the outside

interventions. Fig 3 gives a snapshot of our current digital healthcare ecosystem mode, emphasizing avatar interactions, ad-hoc organizations and the virtualization of instruments from the real world.

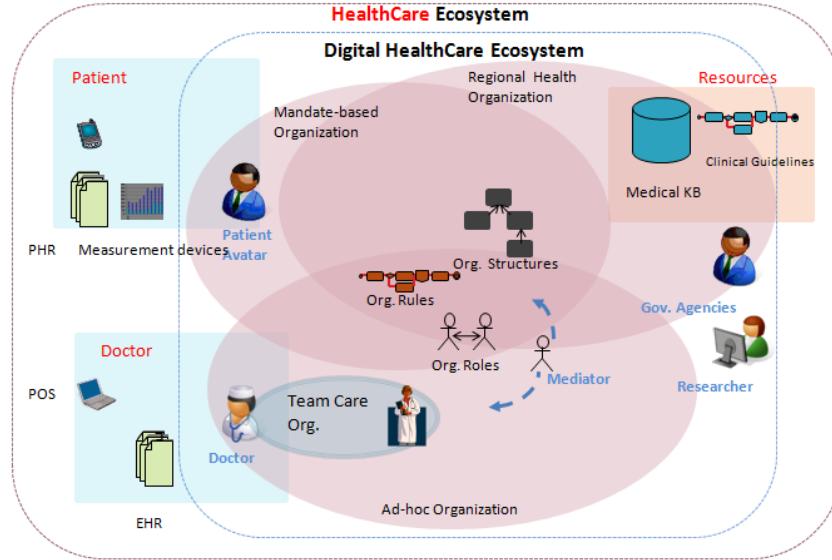


Fig. 3. Digital healthcare ecosystem

When designing the framework of the DHE we must also keep in mind the overall goals of the whole healthcare system such as the improvement of the public health, lowering the costs associated to healthcare and increasing the quality of the healthcare services. Since direct control as well as internal modifications or visualization of the avatars in this open system is impossible we must provide a superior abstraction, of an overall e-health community organization. The organization provides organizational structures and also organizational rules which express global requirements for the interaction of avatars. The rules can control the performed actions defining which avatars are permitted, obligated and prohibited to execute those actions.

We are not interested only in reflecting the reality but also in finding new solutions in the virtual space and diffusing them in the real world. Such a selection mechanisms works by creating an artificial equilibrium point in the virtual market, a multi-axis space in which we add to the traditional two dimensions: supply and demand, other dimensions: population and individual healthcare. This forces the ecosystem population to adapt in order to meet the new requirements (see Fig. 4).

Another way in which systems can benefit of virtualization is the facilitation of resource discovery. Some resources such as medical knowledge basis can be obstructed from view, hidden under red tape. By exposing them in the virtual space we allow them to be discovered by interested and entitled parties.

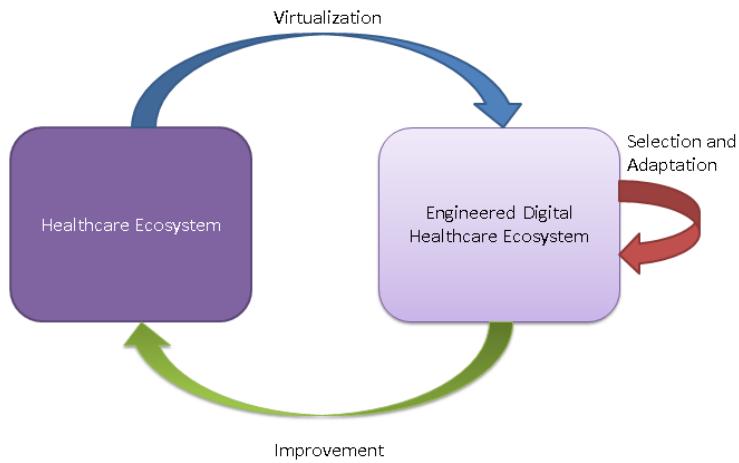


Fig. 4. Virtualization feedback loop

5. Agentification of the healthcare ecosystem

In our case we call “agentification” the process of applying the intelligent agent paradigm to the digital healthcare ecosystem conceptual model in order to design and implement the digital species as autonomous, pro-active software agents, existing and interacting in an self-organizing digital environment.

The main obstacle to switching to the agent model is that contemporarily there is not yet a sound supporting agent technology or complex, integrated development tools. Also, due to the lack of widespread use, at least in the industrial area, there are no consolidated practices, pragmatic software development models, metrics and methodologies with a success record. The research work on agents has concentrated so far in theoretical aspects, as most researchers have had a background in AI-fields, cognitive science and not so much originating from the software engineering fields. [16][17][18]

In order to populate the agent-based DHE we analyzed the functionalities of and derived agent roles from the roles of persons in the health organizations and of organizations themselves.

We structured the agent population in different layers and according to their functionalities we identified several agent categories:

1. *Interface agents* that are responsible for communicating with external systems, either human users or legacy software applications that need to be integrated in the agent ecosystem. These agents should be “bilingual”, meaning to understand both agent languages and the specific interfaces of the adapted systems. They are also responsible for displaying information to the user using graphical interfaces.

2. *Control agents* that solve problems by coordinating and controlling other agents, sometimes specifying plans for problem-solving. In this category we have several agent types: negotiators, workflow monitors and organizers. The agents act on behalf of the citizen’s concerns by adding information in an authoritative, non redundant view on her/his health state and clinical history and devising actions to be carried out by the citizen. They also have the ability to interact with other digital components within the DHE, enter contextual alliances and participate in business process. A special case of control agent is the clinical workflow engine. In our approach a care plan is modeled as a business process. Once a care plan is included in the patient record after a therapy prescription service, its execution is assigned to such a clinical workflow engine agent which supervises the realization of the care plan.

3. *Processor agents* should receive the tasks from the control agents and execute them using the available resources.

4. *Information resource agents* should be expert agents, exposing the contents of a dedicated ontology or knowledge base to other agents. They must be able to answer queries, for example an agent exposing a diabetes knowledge base can receive the description of the symptoms, translate them to the ontology vocabulary, query the ontology and return a match, if one exists.

5. *Query agents* that provide structured information on request by accessing heterogeneous and distributed collections of information sources.

6. *Organizational mediator agents* are created whenever an ad-hoc organization is created, to support a multidisciplinary team treating a particular patient. These agents coordinate the actions of the involved provider agents, enforcing the protocols of communication and managing the encounters between avatars.[7]

7. *Supervisor agents* which monitor the interactions of agents. They are tasked with super-organizational purposes such as improving the public health and increasing the quality of medical services. By monitoring the interactions they can synthesize trends over longer periods of time.

8. *Utilitarian service agents* that carry out tasks useful for the other agent categories. In this category there are low-level service agent types: brokers that help to match agents that request services with agents that provide services, access enablers that verify permissions for accessing a resource or exchanging messages

with other agents, or multicasters that help to dispatch notifications according to their dispatching policies.

These agents can be “instantiated” by their providing organization and dispatched where they are necessary.

We use a component-oriented approach for defining the internal architecture of each agent in the MAS.

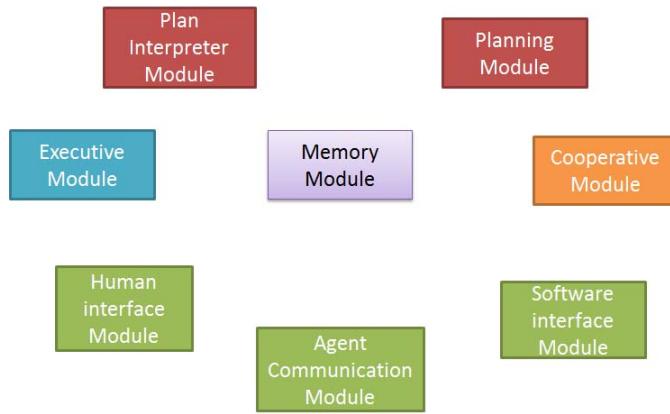


Fig. 5. Agent components

We call agent manufacturing the process of creating new agents. We use this term in order to underline the fact that this should not be an ad-hoc procedure but instead should be based on reliable software factories that supply us with the needed off-the-shelf standardized software components (see Fig. 5) that are combined to create a new agent instance when we want to agentify a new entity. [8]. Based on the type of the entity, a template specifying the necessary components are selected, the software factories instantiate those components which are combined in a new agent.

Not all the components in the agent have the same lifespan. Some, for example the memory module, exist as long as the agent exists. The context-dependent modules, providing the interfaces to the workspace are destroyed each time the agent passes from one workspace to another.

In such a way from a finite number of components we can obtain an infinite number of agent types, customized to each situation. These components can be:

1. Human interfaces: Graphical Interfaces presented to the user.
2. Software interfaces: Ports to other software applications

3. Communication: Components able to code and decode from Agent Communication Language such as FIPA. Communication module accepts and interprets messages and requests originating in the environment; it also sends messages and requests to other agents in the environment.

4. Cooperative: Components handling negotiation, coordination, cooperation between agents.

5. Executive: Components executing tasks and procedures.

6. Memory modules: Components holding the memory of the agent: past actions, past goals and past interactions. The Memory structure is specific for each agent type. With the Memory part the agent is embedded in the environment, that is “senses” or “provokes” changes in the environment. These changes are fundamental for inter-agent communication.

7. Planning modules: may identify a set of goals and produce a plan to reach them. The plan is a process description that can satisfy the goals after its execution.

8. The Plan Interpreting Modules use the plan to keep track of the plan execution and to identify the next action to be carried out.

In this scenario when an agent enters a new workspace, the environment provides the interface components, necessary for sensing and acting with the environment. The other components (planning, execution) are persistent, traveling with the agent from one workspace to another.

The overall architecture for the agentified DHE is shown in Fig. 6. The agent environment supplies the needed components using software factories and also supplies the communication middleware with its required services. Agents have a layered, component-based architecture. Agents can enter organizations, in which case their purpose is to enact a role specified in the organization structure.

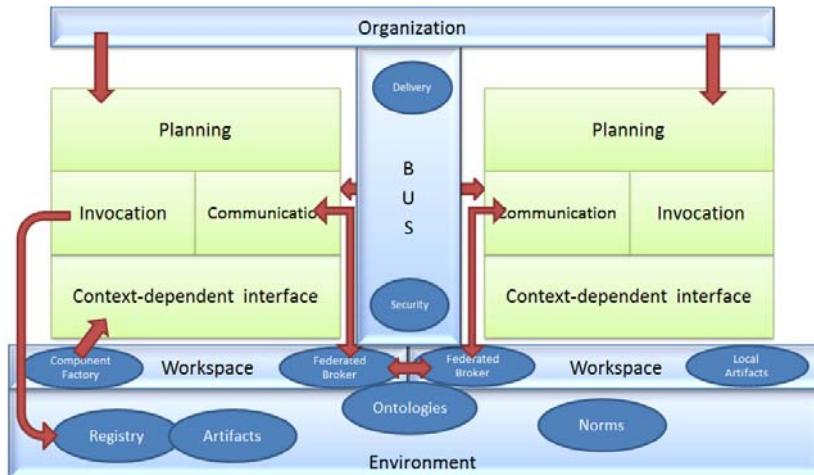


Fig. 6. MAS architecture

6. Implementation

The DHE implementation in this project had to take into consideration a number of factors:

- To simulate the whole digital healthcare ecosystem is a huge undertaking, with a scope too large for a doctoral thesis. That is why we have given much consideration in choosing a representative scenario, simple enough to be implemented in the time frame but complex enough to prove the theoretical premises.
- An important part of the digital ecosystem is made up by the legacy software applications which need to be agentified and integrated in the environment. Adapting an application to a different paradigm is not simple as we need to formalize its knowledge, which usually is not even documented but embedded in the code. For this reasons we have chosen to agentify a single medical application, an electronic medical record (EMR) which had the advantage of producing HL7 compliant documents, so we respect the open-standards approach in digital ecosystems.
- The virtual healthcare record had to be built from scratch as we had found no implementation complex enough for our longitudinal approach to EHRs. However in order to simulate that such an application existed we had chosen a service oriented approach for the implementation.

Starting from these considerations we have developed a “micro” digital healthcare ecosystem consisting mainly from the patient and doctor avatar, in a digital environment populated with agents used by those avatars: boundary agents, workflow agents, interface agents for the medical devices, social agents etc.

The virtual healthcare record (VHCR) is implemented as a service, introduced in the environment with the help of a boundary agent that has a dual-role: to interpret SOAP into ACL messages and vice-versa and to check the permissions for other agents which require interaction with VHCR.

The main source of medical information that populates VHCR comes from our legacy application. We attach an adaptor agent to the application which communicates with the doctor avatar. When a visit is made, the information is added in the EMR, translated and sent to the doctor avatar which chooses whether to integrate it in VHCR (by signing it). The task of integrating heterogeneous information in VHCR, in fact the health state representation of the patient, falls upon the patient avatar.

To show some of the properties of digital ecosystems such as self-organization we have chosen a scenario involving a chronic disease, diabetes, which needs a multi-disciplinary team of care givers. When a health goal appears from the change in the perceived health state of the patient, that goal is sensed by the environment and, in the background, a team of caregiver avatars is formed and

presented to the patient for approval. The team formation algorithm is not trivial as it needs to take into consideration the health state of the patient, the specialties of the doctors and not in the least, the history of other team structures formed around the same patient.

For the actual technologies we have chosen to implement VHCR as an Enterprise Java Bean 3.1 application that exposes SOAP-based web services [19]. The persistence is assured by using Java Persistence API, implemented by EclipseLink on an embedded JavaDB. The module is deployed on a Glassfish 3.1 server. For the MAS we have chosen JADE [20], 4.1 version as it is the most used agent-based middleware, conforming to FIPA standards. Currently our agents are not designed to be mobile.

7. Conclusions

The contamination of the real to the virtual in analyzing the digital healthcare ecosystems will generate in time a reflection of the virtual in the real, when solutions and resources discovered in the digital world will make their impact in the real world. Also, the transition to a digital healthcare ecosystem will also promote an increase in the quality of e-Health care services by creating a competitive open, standards-based market, where multiple vendors can publish their interoperable services and products and where those services and products can be discovered and delivered.

By choosing a component-based approach to our architecture, where composite agents are built from standard software components, we are increasing software reuse and also encourage vendors to participate in producing particularized solutions, for the heterogeneous application medium, which can be integrated in the digital environment.

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