Multi-Agent Systems for e-Health: Recent Projects and Initiatives

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ABSTRACT

Multi-agent systems have been notably contributing to the development of the theory and the practice of high-speed, mission-critical, content-rich, decentralized information systems where mutual interdependencies, dynamic environments, uncertainty, and sophisticated control play a singular role. Multi-agent systems can be considered a suitable technology for the development of healthcare applications where the use of loosely coupled and heterogeneous components, the dynamic and distributed management of data and the remote collaboration among users are often considered the most relevant requirements. This paper provides a structured enumeration of the most notable recent attempts to use multi-agent systems for healthcare.

1. INTRODUCTION

Multi-agent systems are one of the most interesting areas in software research and they have been importantly contributing to the development of the theory and the practice of complex distributed systems. In particular, they have shown their potential to meet critical needs in high-speed, mission-critical, content-rich, distributed information systems where mutual interdependencies, dynamic environments, uncertainty, and sophisticated control play a notable role [18]. Healthcare applications can take outstanding advantage of the intrinsic characteristics of multi-agent systems because of notable features that most healthcare applications share: *(i)* they are composed of loosely coupled (complex) systems; *(ii)* they are realized in terms of heterogeneous components and legacy systems; *(iii)* they dynamically manage distributed data and resources; and *(iv)* they are often accessed by remote users in (synchronous) collaboration [4][34].

The goal of this paper is to describe the main reasons why multi-agent systems are considered one of the most interesting technologies for the development of healthcare applications and services. First, it provides some guidelines intended to help identifying the kinds of healthcare applications that can truly take advantage of the features of multi-agent systems. Then, it presents some of the most important international projects that used multi-agent systems in the healthcare domain.

2. WHY MAS FOR e-HEALTH?

There is common agreement in the field that the buzzword e-health was introduced around 1999 as a consequence of the *e-** mania to talk about the provision of healthcare services through the Internet. Notably, such a buzzword was heavily promoted by the industry and by application and service vendors and soon the academic community started using it instead of the over-abused term telemedicine. Such a widespread adoption of this new buzzword was so wide and deep that anything that had to do with technology and health was quickly included. In order to clarify the obvious misunderstandings that immediately arose and to support such an important idea, the European Commission itself felt the urge to provide a common and generally acceptable definition of the word e-health as: "*the use of modern information and communication technologies to meet needs of citizens, patients, healthcare professionals, healthcare providers, as well as policy makers.*" [15]

Besides the clarity–or possibly the confusion, someone may say–that the mentioned definition created, it is common understanding that e-health uses ICT for the provision of health-related services to sparse users. This pushed interaction and communication as central to e-health and it immediately promoted multi-agent systems as ideal candidates to support next-generation e-health services and applications.

Similarly, e-health deals naturally with mobile users, e.g., in teleassistance scenarios, and it is common understanding that e-health should transparently accommodate fixed and mobile users. So called m-health is yet another buzzword that has been recently proposed to stress this fact: m-health services should be accessible anyone, anywhere, anytime, anyhow, and any-*. Moreover, e-health mainly address mobile scenarios where devices are used to collect, transmit and process vital patients' data, e.g., heart rate and blood pressure, in real time. Such systems are especially important in applications that remotely monitor patients with chronic ailments or in homecare. Broadly speaking, such systems are designed to access medical information in a mobile and ubiquitous setting. This access may be either *(i)* the retrieval of relevant medical information for use of healthcare practitioners, e.g., a hospital doctor on his/her ward round; or *(ii)* the acquisition of patient-generated medical information, e.g., telemonitoring the patient's health state outside the hospital. In both cases, it is extremely important to ensure that the person retrieving or generating information could interact with a ubiquitous and pervasive e-health system without any obstruction or adaptation of the normal workflow or style of working. The most notable characteristic that such systems should exhibit are: *(i)* Context and location awareness are to be smoothly integrated, i.e., the access and the visualization of health-related information always depend on the overall contexts of the patient and of the user [8], *(ii)* fault-tolerance, reliability, security and privacy-awareness are a must in order to accommodate the strict requirements of all healthcare applications, *(iii)* effective mobile devices are to be used to provide access to relevant health-related information independently of the current physical location and physical condition of the user, and *(iv)* unobtrusive sensor technology is needed to enable the gathering of physiological information from the patient without hampering his/her daily life.

All in all, mentioned requirements immediately recall the characterizing features of multi-agent systems and it comes with no surprise that many ubiquitous and pervasive e-health systems are realized using multi-agent abstractions and technologies. In particular, the mentioned tool JADE and its lightweight version JADE-LEAP [6] do take special care of transparently and dynamically allocating users and agents on heterogeneous network of different types of devices.

An important issue in e-health is about supporting the interoperability of (legacy) medical information systems in order to enable the integrated provision of services for accessing information from different, remote sources. The dream of a single, universally-accepted middleware supporting the development of new services together with the renewal of legacy services was quickly abandoned and nowadays recent technologies that were originally intended to support the (semantic) interoperation between heterogeneous services are commonly adopted in practice. This, again, emphasizes the role of multi-agent systems for providing important contributions to e-health because of the inherent semantics-awareness of the interaction between agents, which make them ready to deliver semantic interoperability.

Another important issue that most e-health services address regards the possibility of jointly supporting professionals in their highly specialized work. Computer-Supported Cooperative Work (CSCW) is already common practice in telesurgery and teleassistance and it seems an important ingredient of next-generation e-health services. Notably, the inherent cooperative nature of agents and the very fact that many CSCW technologies are already based on agents is another important contribution of multi-agent systems to e-health.

Similarly, the central venue that security and privacy-awareness have in multi-agent systems again stresses their importance of them with respect to e-health. In the agents realm, the issues of privacy-awareness are treated under the umbrella of the more expressive notion of trust. Likewise, e-health strongly remarks the importance of preserving confidentiality and guaranteeing a high level of security for classified information about patients.

Even if the mentioned facts regarding the adoption of multi-agent systems for next generation e-health services and applications can be convincing, we now try to sustain our statement by adapting the well-known grouping criteria proposed in [5]. We say that multi-agent systems contribute to next-generation e-health from three points of view: *(i)* improving the quality of healthcare; *(ii)* facilitating the access to healthcare; and *(iii)* reducing costs.

The most important contribution that multi-agent systems provide to the overall quality of healthcare relies essentially on the possibility of feeding highly specialized healthcare professionals with the right information, at the right time, tailored to the patient. The proactive nature of agents and their semantic interoperability support such a need with the possibility of feeding users with information acquired from diverse sources and tailored to the concrete patient at hand. Thanks to the computerization of health records, that is now common practice in Western Countries, the transfer of complex health records globally and quickly increases the accessibility, unifies the information at every stage of complex healthcare processes and improves care continuity. Moreover, the longstanding tradition of expert systems that still lives behind the scenes of multi-agent systems can support healthcare professionals in using the provided information for taking the right decisions at the right time. Finally, the transparent integration of mobile terminals helps collecting data to quickly support contextualized healthcare decisions.

Notably, the scenario of allowing a quick and contextualized access to healthcare-related information from anywhere, at anytime and in the most appropriate way can promote the long-waited universality and equality of access to healthcare, especially for geographically or socially isolated patients. Such cases are uncommon and they may seem visionary for the current lack of supporting infrastructures, e.g., universally-accessible communication networks and power supplies, but the inherent decentralization that is always assumed in multi-agent systems is vital to facilitate the access to healthcare also in everyday scenarios. This is the case of, e.g., homecare to elderly, disabled or chronic patients. The widespread adoption of multi-agent systems at homes helps reducing medical visits and related waitlists drastically. Moreover, the proactive nature of agents assists in creating a trusted link between agents and patients by having agents constantly pushing valuable information to patients, with no need of explicit demands. Agents are good tools to help patients following preventive strategies and supporting self-care on a day-by-day basis.

The last grouping criterion in [5] is about cost reduction of healthcare processes. This is an issue of notable importance for the inherent costs of quality healthcare and multi-agent systems are beneficial also from this point of view. The mentioned possibility of agents to provide the right information, at the right time, tailored for the patient supports efficiency in the overall management of treatments. Moreover, the semantic interoperability of agents enables instant acquisition of information from its natural source, with minimal (if not null) pass of information along chains of intermediaries. Finally, the trusted and privacy-aware support that agents provide to healthcare processes is a valuable means to speed up and optimize many administrative procedures. All in all, we can summarize the contribution that multi-agent systems provide to healthcare from the point of view of cost reductions with an incisive proposition: earlier assistance and structured prevention of the causes of further care.

3. RECENT PROJECTS AND INITIATIVES

As is described above, multi-agent systems can become a key ingredient of the next-generation e-health services and applications, however, in the last ten years they are already used for realizing e-health applications and, in particular, for realizing assistive living, diagnostic, physiological telemonitoring , smart hospital and smart emergency applications. In the following, some of the most interesting applications are introduces.

3.1 Assistive Living Applications

The integration of smart-home automation is an essential aspect of assisted living for the elderly or for impaired people [29][36][31]. All projects in this domain are notably challenging because they need to naturally accommodate many, if not all, the challenging aspects of the kinds of applications mentioned above. Elderly people tend to suffer from at least one chronic disease, which requires telemonitoring. Additional age impairments make independent living at home difficult and therefore assistance for daily activities is required. Moreover, the additional context information provided by a smart-home environment enhances a better interpretation of physiological sensor information, e.g., whether the patient is running or sleeping has significant influence on the blood pressure. All in all, multi-agent systems are the common denominator of the kinds of uses that we listed above and this is the reason why we believe that they are a key factor for the coherent and successful development of assistive living applications. Two of the most interesting projects are: CASIS [25] and K4CARE [26].

CASIS [25] is an event-driven service-oriented and multi-agent system framework whose goal is to provide context-aware healthcare services to the elderly resident in the intelligent space. CASIS framework allows remote caretakers, such as concerned family members and healthcare providers, to closely monitor and attend to the elder's physical and mental well-beings anytime, anywhere. The smart environment interacts with the elder through a wide variety of appliances for data gathering and information presentation. The environment tracts the location and specific activities of the elder through sensors, such as pressure-sensitive floors, cameras, bio-sensors, and smart furniture. Meanwhile, the elder receives multimedia messages or content through speakers, TV, as well as personal mobile devices. The caregivers may access the elder's health and dietary information through any Web enable device like a PC or PDA. Context-aware computing enables the environment to respond at the right time and the right place, to the elder's needs based on the sensor data collected. The environment is further equipped with integrated control for convenience, comfort and safety. In particular, CASIS is able to infer the status of the elder and performs appropriate actions. For example, upon sensing that the elder has fallen asleep, it turns off the TV, and switches the telephone into voice mail mode. It informs and plays back any incoming messages when the elder wakes up.

K4CARE [26] is a research project whose main objective was to combine healthcare and ICT experiences coming from several western and eastern European countries to create, implement, and validate a knowledge-based healthcare model for the professional assistance to senior patients at home. The main step of the project was to develop a healthcare model to guide the realization of an integrated system of healthcare services for the care of the elderly, the disabled persons, and the patients with chronic diseases. The interaction between health professionals, computer scientists, technology centres, and SMEs has been crucial to define the model and providing detailed information about the selected prototype services. The K4CARE model provides a paradigm easily adoptable in all European countries, being all the proposed structures filtered according to national laws.

3.2 Diagnosis

Diagnosis is probably the first area of healthcare where computer systems and artificial intelligence techniques where used [9]. Diagnosis support systems oftnn need the integration of different sources of data and the on-line or off-line collaboration of different kinds of users. These features make multi-agent systems a reference model and technology for their realization Three of the most interesting projects that used multi agent systems for the realization of diagnosis applications are: IHKA [21], OHDS [20] and HealthAgents [13].

IHKA [21] is a healthcare knowledge procurement system based on the use of multi-agent technologies. This system is based on six different agent types. These types are the user interface agent, an agent to convert the search result into a viable format for passing to the UI agent, a query optimising agent which optimises the query, the knowledge retrieval agent that performs the query, the knowledge adaptation agent to adapt the knowledge to the current circumstances and the knowledge procurement agent which if all else fails searches the web for the knowledge. In particular, IHKA features autonomous knowledge gathering, filtering, adaptation and acquisition from some healthcare enterprise/organizational memories with the goal of providing assistance to non-expert healthcare practitioners.

OHDS [20] is a system that supports the doctors in the diagnostic, treatment and supervision processes of the evolution of new epidemics, based on the exploration of all data pertinent to each case and on the scientific data contained in various professional databases. OHDS combines the advantages of the holonic paradigm with multi-agent system technology and ontology design, for the organization of unstructured biomedical research into structured disease information. Ontologies are used as 'brain' for the holonic diagnostic system to enhance its ability to structure information in a meaningful way and share information fast. A fuzzy mechanism ruled by intelligent agents is used for integrating dispersed heterogeneous knowledge available on the web and so, for automatically structuring the information in the adequate ontology template.

HealthAgents [13][21] is a research project with the goal of improving the classification of brain tumours through multi-agent decision support over a secure and distributed network of local databases. HealthAgents does not only develop new pattern recognition methods for distributed classification and analysis of in vivo MRS and ex vivo/in vitro HRMAS and DNA data, but it also defines a method to assess the quality and usability of a new candidate local database containing a set of new cases, based on a compatibility score. Using its multi-agent architecture, HealthAgents applies cutting-edge agent technology to the biomedical field and it provides an infrastructure for the so called HealthAgents network, a globally distributed information and knowledge repository for brain tumour diagnosis and prognosis.

3.3 Physical Telemonitoring

Telemonitoring, the continuous monitoring of patients at home, is becoming an extremely important application domain in the context of e-health, mainly because of the progression of chronic ailments in the aging society [32]. First, such applications enable healthcare institutions to manage and monitor the therapies of their patients. Second, they serve as instrument for performing large-scale medical researches and studies. Third, they support the timely activation of emergency services in case of severe health conditions. Due to the nature of such applications, that are continuously monitoring physiological signals, unobtrusiveness and mobility of the patient are key requirements. Moreover, these applications can offer additional comfort services as by-product, like assistive services, information services and communication services, which leads us naturally to the adoption of multi-agent systems for the realization of physiological telemonitoring applications [40]. Five of the most interesting projects that use multi-agent systems are: MobiHealth [33], U-R-SAFE [44], AID-N [17], MyHeart [2] and SAPHIRE [27].

MobiHealth [33] is an innovative software platform for Body Area Networks (BANs) is the heart of the architecture of project MobiHealth (MobiHealth), which was funded by the European Commission under the 5th Framework Programme (FP5). It provides plug and play sensor connectivity and it handles related issues such as security, handovers and quality of service. It enables monitoring, storage, and wireless transmission, by means of GPRS and UMTS technologies, of vital signals data coming from the BAN of the patient. Possible hardware platforms for this architecture are PDAs or programmable mobile phones which can serve as Mobile Base Units (MBUs).

The investigated application scenario is telemonitoring of patients at home. Vital signals are measured and are transmitted along with audio and video to healthcare service providers. The MobiHealth service and application platform enables monitoring, storage and transmission of vital signs data coming from the patient BAN. The platform supports flexible personalization of services and ensures appropriate intervention in response to certain conditions or combinations detected in the vital signs measurements.

U-R-SAFE [44] is a research project with the goal of realizing a telemonitoring environment for elderly people and patients with chronic diseases. The project developed a portable device which continuously monitors physiological signals (heart activity, oxygen saturation, and fall detection) and which is able to send an alarm to a medical center if an abnormality is detected. The technology issues tackled in this project cover sensor devices and wireless communication. The concept is to have the elderly person wearing medical measuring devices, all connected via short range Wireless Personal Area Network (WPAN) to a central, portable electronic unit, the so called Personal Base Station (PBS). The short range wireless connection is done using the Ultra Wide Band technology. It is worth noting that, at home or at the hospital, two wireless networks are interconnected. The first is the WPAN worn by the person and the second is the wireless indoor LAN, installed in the house or at the hospital, which allows the PBS communicating via a dedicated gateway to the fixed-access network using radio links.

AID-N [17] is a light-weight wireless medical system for triage. The overall goal of the AID-N electronic triage system is to efficiently gather and distribute information on the vital signs and locations of patients in an extremely fault tolerant manner. Typically, monitoring systems like AID-N consist of *(i)* a central server that medical doctors use to verify the overall conditions of patients, and *(ii)* portable clients–one for each patient–that patients use to send information about their condition. Such instruments delegate to the patient the task of providing relevant data obtained from classical sensors. Moreover, monitoring devices are not normally capable of proactively operating to autonomously detect anomalies in the conditions of patients, i.e., they always need the direct intervention of the patient. Finally, such devices are quite general and they are not able to adapt to the very specific needs of each patient. In other words, such systems would really benefit from an agent-oriented approach that would support personalization and proactivity.

MyHeart [2][35] is a research project whose focus was on preventing cardiovascular diseases by intensively applying e-health applications. The work focused, in particular, on the telemonitoring scenario, where sensors integrated in clothing are used to monitor heart activity and the physical activity of the patient. This project emphasizes the importance of specialized sensor and hardware devices to allow unobtrusive measurements. The approach is therefore to integrate system solutions into functional clothes with integrated textile sensors. The combination of functional clothes and integrated electronics to process them on-body defines what MyHeart consortium calls Intelligent Biomedical Clothes. The processing consists of making diagnoses, detecting trends and react on it. MyHeart also comprises feedback devices that are able to interact with the user as well as with professional services.

SAPHIRE [27][41] is a research project whose goal was to develop a multi-agent system for the monitoring of chronic diseases both at home and at hospital using a semantic infrastructure. The system is capable of deploying and executing clinical guidelines in a care environment including sparse care providers having heterogeneous information systems. The SAPHIRE multi-agent system addresses such challenges through an enabling semantic interoperability environment.

3.4 Smart-Hospital, Smart-Emergency Applications

When located at caregiver's site, e-health applications are often known as smart-hospital applications. Such applications try to improve the daily activities of doctors and nurses. This is commonly done by providing tools to access patient records or, more generally, clinical information systems, as well as to schedule and track patients and hospital resources in a wireless, mobile, and context-aware manner. It is worth noting that recent projects introduce the use of RFID technology to further improve these applications, as exemplified in the Jacobi case study [16]. Another case of e-health at the caregiver's site regards emergency management by means of mobile devices. Emergency physicians are able to access the records of their patients in advance while they are still in the ambulance car approaching the location of the patient. If we also consider the triggering of emergency situations and access of current physiological signals, these applications spans the bridge between the caregiver's and patient's site. Three of the most interesting projects that use multi-agent systems are: ERMA [30], Akogrimo [1] and CASCOM [42].

ERMA [30] has the purpose of providing meaningful diagnoses and intervention suggestions to the healthcare personnel acting on behalf of the patient in the cases of emergency trauma with particular emphasis on types of shock and stabilization of arterial blood gases. This system ERMA is based on a set of agents that act as a collaborative team of specialists to realize the monitoring and diagnostic infrastructure for dynamically collect filter and integrate data and reasoning about them through a hybrid approach of fuzzy logic, causal Bayesian networks, trend analysis and qualitative logic.

Akogrimo [1] is a research project whose main goal is the integration of the next generation Grids (NGG) with the next generation networks. The application scenarios of Akogrimo cover smart hospitals, telemonitoring and emergency assistance. The Akogrimo NGGs are able to deal with an environment with rapidly changing context such as bandwidth, device capabilities, and location. Furthermore the architecture of Akogrimo can be immediately deployed in unlicensed mobile access environments such as hot-spot infrastructures, because it assumes a pure IPbased underlying network infrastructure. Target users of an Akogrimo healthcare information system are *(i)* people demanding mobile ad-hoc and pervasive healthcare services, e.g. due to emergencies or chronic diseases; and *(ii)* healthcare service suppliers/institutions, i.e., stationary or mobile professionals, including healthcare advisors, pharmacies, nursing services, hospitals, emergency service devices and emergency stations. The reference scenario of Akogrimo covers objective like: *(i)* early recognition of heart attacks and fast treatment by combining vital parameters monitoring; *(ii)* aberration and emergency detection; and *(iii)* subsequent rescue management.

Agents are spread all over in the architecture of Akogrimo, ranging from the end-user application, i.e., Akogrimo Personal Assistants, to infrastructural agents supporting interactions between personal assistants.

CASCOM [11][42] is one of the most recent attempts to bring the notable characteristics of agents to e-health. CASCOM is a technology-driven project that brings together three notable new technologies: multi-agent systems, Semantic Web services and peer-to-peer middleware in the scope of mobile and context-aware environments. It finds its motivations in a healthcare scenario that was ran in many occasions throughout all Europe.

4. CONCLUSIONS

Multi-agent systems have been proved as one of the most interesting technology for the development of complex and distributed applications. However, multi-agent systems are not only a development technology, rather they provide a novel level of abstraction that is concretized into different technologies depending on the concrete needs of applications. This allows describing various projects and applications that concretely use diverse technologies in terms of agents and multi-agent systems. Healthcare is a vast open environment characterized by shared and distributed decision making and management of care requiring the communication and coordination of complex and diverse forms of information between involved organizations and people. Therefore, both multi-agent systems and healthcare can have advantages from their coupling: multi-agent systems have the suitable features for the modelling and realization of current and future health care applications; healthcare scenarios offer the suitable requirements for experimenting at best the multi-agent technologies and, so, for giving a great contribution to their evolution and success.

According to Altman [2], one of the ten infrastructure challenges that Artificial Intelligence has to face to provide valuable contribution to healthcare regards having medical records "*based on semantically clean knowledge representation techniques.*" Agents not only provide the needed tools to turn such a challenge into reality, but they also provide a clean way to make such records available anywhere, at any time. This is a notable improvement of the proposed challenge and agents are ideal means to achieve it. Moreover, we agree with [4] and we believe that a key component of the "*smart use of computation*" that authors mention will be the use of agent technology. Agents will improve healthcare organizations and will also support doctors and caregivers. However, we also agree on the mentioned issues regarding the impact of the use of agent technology with patients, which will not only be an improvement but a radical change in how healthcare and assistance will be provided.

There are also many technical problems associated with the development of multi-agent systems for healthcare; some of them are identifiable in any application domain, such as user expectations and acceptance, and lack of centralised control; others are typical of the healthcare domain, such as legal and ethical issues like privacy, integrity and authentication in the exchange of patient information between agents. The solution of such problems will be possible with the evolution of multi-agent systems technologies and the definition of precise rules for their application in some specific fields. Multi-agent systems are still evolving towards a complete maturity and the variety and complexity of e-health scenarios make it one of most interesting application fields able of verifying the advantages of their use and of conditioning their evolution. Moreover, the success of multi-agent systems in e-health applications will be also due thank to the current work on the integration of multi-agent systems with some emergent technologies like, e.g., Web services [19][38], the Semantic Web [12][23] and workflows [10][37], that are already and/or will be fundamental components of e-health [7][43].

Unfortunately, the adoption of agent technologies within e-health is taking place quite slowly and, despite the number of research projects on the topic, this by far an assessed practice. We believe that the main reasons for this are not in the agent technology itself, which is generally well accepted; rather they originate from the inherent difficulties of having ICT accepted in healthcare from the technical, social, ethical, political, legal and economical points of view. This is a well discussed topic in the literature and interested readers can refer to some notable works [5][14][24][28][39][45].

Finally, the distance between the actual research and the real needs of the health system poses several problems to a wide adoption of ICT. The lack of data and methodology for the economic evaluation of e-health projects (e.g. e-health services reimbursement is not well defined) is an obstacle for the clinical routine implementation of the e-health systems as well as to obtain funds for new e-health projects.

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