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SYMPOSIUM

Utilizing Information Technologies for Lifelong Monitoring in Diabetes Patients

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Abstract

Background:

Information and communication technologies have long been acknowledged to support information sharing along the whole chain of care, from the clinic to the homes of patients and their relatives. Thus they are increasingly being considered for improving the delivery of health care services also in light of clinical and technological achievements that propose new treatments requiring a tighter interaction among patients and physicians.

Methods:

The multiagent paradigm has been utilized within an architecture for delivering telemedicine services to chronic outpatients at their domiciles and enforcing cooperation among patients, caregivers, and different members of the health care staff. The architecture sees each communication device such as a palmtop, smart phone, or personal digital assistant as a separate agent upon which different services are deployed, including telemetry, reminders, notifications, and alarms. Decoupling services from agents account for a highly configurable environment applicable to almost any context that can be customized as needed.

Results:

The architecture has been used for designing and implementing a prototypical software infrastructure, called LifePhone, that runs on several communication devices. A basic set of services has been devised with which we were able to configure two different applications that address long-term and short-term monitoring scenarios for diabetes patients. The long-term scenario encompasses telemetry and reminder services for patients undergoing peritoneal dialysis, which is a treatment for chronic renal failure, a diabetes complication. The short-term scenario incorporates telemetry and remote alarms and is applicable for training patients to use an artificial pancreas.

Conclusions:

Our experiments proved that an infrastructure such as LifePhone can be used successfully for bridging the interaction gap that exists among all the components of a health care delivery process, improving the quality of service and possibly reducing the overall costs of health care. Furthermore, the modularity of services allows for more complex scenarios encompassing data analysis or even involving actors at multiple institutions in order to better support the overall health care organization.

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Abbreviations: (AP) artificial pancreas; (APU) artificial pancreas unit, (EHR) electronic health record, (ICT) information and communication technology

Keywords: artificial pancreas, reminders and alarms, self-monitoring, telemonitoring

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Introduction

Diabetes is one of the most common chronic diseases in the world. Diabetes affects more than 240 million adults and shows an ever increasing incidence that is expected to reach epidemic proportions by the year 2025, a total figure of over 380 million people.[1] The costs for its treatment, which already reached over $170 billion in 2007 in the United States only,[2] are therefore expected to likewise increase by 2020.

As with all chronic patients, people with diabetes are required to self-manage their disease through a constant monitoring and assessing of their illness state and to independently take the most appropriate action each time.[3] This effort is aimed at achieving the best glycemic control as possible, as this reduces the probability of developing diabetes-related complications in the long term.[4] More specifically, although hypoglycemia events have long been considered as the most important threat to fight, because they pose an immediate risk to the patient's life, the consequences of inadequate control of hyperglycemia over several years may have an even greater social and economic impact.[5] Diabetes patients who undergo frequent hyperglycemia events may develop serious complications such as: permanently harming various organs such as the retinae, ending up in a total vision loss, or the kidneys, leading to a total renal failure; lower limb ulcers and amputations; or gastrointestinal and cardiovascular dysfunctions. Therefore, although it is particularly challenging, finding new ways of enforcing proper metabolic control is crucial[6] because it results in a lifelong treatment of the disease.

Rather interestingly, there is a growing effort in the scientific community concerning the identification of new paradigms of care and the implementation of systems for efficiently and effectively supporting remote/home treatment. All models try to enforce a better compliance with the therapeutic protocol assigned and to avoid lessening the health care staff awareness about a patient's chronic condition as often happens with outpatients. Many of those efforts utilize information and communication technology (ICT), promoting novel types of interaction among the involved authors. They concentrate either on the definition of shared standards and valuable architectures[7] as well as on the implementation and evaluation of prototypes for educating, consulting, remote monitoring, and data analysis.[8,9]

This article capitalizes on research concerning telemedicine applications that use multiaccess systems[10] and merges them with the methodologies investigating distributed and multiagent systems. Based on the experience gained in a small-scale implementation of a telemedicine system employing mobile devices,[11] we generalize the approach and propose a general architecture for remote management of chronic outpatients.

Methods

Many of the past efforts available in the literature and aimed at devising a telemedicine infrastructure utilizing ICT for remote patient care have been loosely based on a client–server architecture that comprises two different components, a medical unit and a patient unit.[12,13] The former is located at the clinical site. It acts as a concentrator that collects data remotely sent by patients and makes those data available to treating physicians for review. The patient unit is located instead at a patient's home and is used directly by the patient for manually entering data, for automatically acquiring data supplied by connected instruments, or for additional tasks such as getting advice from or messaging with the staff. While this architecture certainly supports data exchange, it is not able to capture the knowledgeable needs of all the parties involved in a health care giving process. Moreover, the partitioning into two opposite halves, each one addressing a fixed set of functionalities, does not provide the required flexibility. Almost any treatment process also sees the involvement of a caregiver supporting the patient and providing some sort of supervision on him. Additional actors could also be involved, each one deserving the most specific support required by their role, and even members of the health care staff should not be constrained to access services provided by the medical unit just in an online fashion. Instead, they often feel the need to use some disconnected support, such as receiving alarms or notifications about events concerning their patients in order to promptly undertake any required action.

This is depicted in **Figure 1**, which best captures the knowledgeable flow existing among health care staff, remote patients, and relevant caregivers. Plain data acquisition, which telemedicine services usually considered to be accomplished only by patients, is often augmented by a supervisory task performed by caregivers that may entail sending additional information concerning a patient's state. Furthermore, while the patient receives immediate reminders and notifications about his treatment, the caregiver might be involved in a broader context browsing for educational information describing the habits to be enforced by the patient or receiving notifications and alarms concerning anomalous behavior. On the health care staff side, there is a much greater need for customization, which is addressed by the two links shown in the upper part of the figure. Those links address the structuring and filtering of knowledgeable data in order to make it available to the appropriate recipients according to the organizational role they play.

In order to achieve the required flexibility for our architecture, we adopted the basic assumption of decoupling the notion of *service* from that of *user-interaction* device. More specifically, the latest achievements in ICT resulted in the widespread availability of communication devices with different capabilities, which are shaping a new behavioral paradigm based on computational pervasivity and ubiquity also affecting the way in which medicine is delivered.[14,15] Thus, our architecture has been designed at a rather abstract level in order to avoid any commitment to a particular computational environment or to a fixed set of user-interaction devices. In order to enhance modularity and configurability, we shaped our architecture after a distributed paradigm loosely recalling a multiagent community.[16,17] User-interaction devices are thus not strictly limited in their functionality but can be configured depending on the specific needs of their users, assembling the most relevant services for each situation.

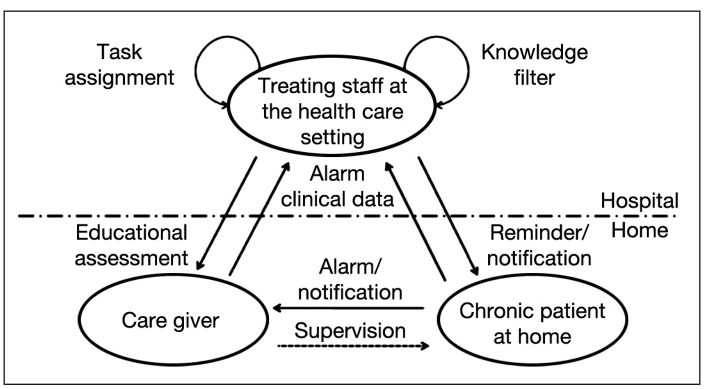

Figure 1. The knowledgeable flow among the several parties involved in a health care delivery process.

The LifePhone Architectural Framework

LifePhone was conceived as an architectural framework following the requirements arising from previous experiences in setting up small telemedicine prototypes for diabetes patients.[18] It serves the purpose of rapidly building up data collection, monitoring, and message delivery services so that it can be utilized as a technological platform supporting short or long-term clinical studies involving chronic patients. The framework strives to be compatible with a large set of communication devices that play the role of customizable agents, which are selected to support user interaction according to the most suitable paradigm. On top of each agent, different services can be deployed, providing data acquisition, monitoring, notifications, and alarms, so that they can act as interaction facilitators for all involved parties. The whole architecture is shown in **Figure 2**, illustrating its structuring on three separate layers.

The bottom layer encompasses the hospital agent that interfaces with the electronic health record (EHR), where all information concerning patient states, treatments, tasks, and any other medical data of concern is stored. Besides interfacing with the EHR, the hospital agent also encompasses a set of services, which are shown as satellite components around it. Each of these services is a software component consisting of two matching pairs. One pair is represented by the several modules hosted by the hospital agent so that they can access any data stored within the EHR, while the second one plugs into the remote agents as shown in the upper part of the figure.

The topmost layer of the figure illustrates how remote agents can be assembled out of several services, each one matching its own counterpart located on the hospital agent. **Figure 2** also shows how various communication devices with different capabilities are meant to host services, thus giving rise to distinct agents. Each service

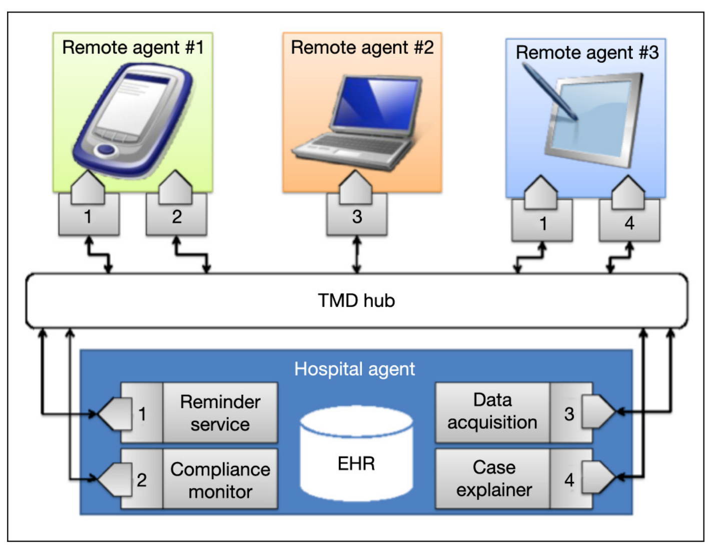

Figure 2. The LifePhone conceptual architecture. TMD, telemedicine.

pair fully characterizes the data to be exchanged between the hospital agent and remote agents, as well as the behavior to be adopted by each party. For example, the reminder service has the purpose of signaling the user when an important event such as taking a measurement or a drug is approaching. The service half located on the hospital agent includes the logic responsible for configuring that service and periodically generating the events, while the matching half located on the remote agent is responsible for actually signaling the user and possibly collecting the acknowledgment reply.

Given that the two pairs of a service completely agree on the data to be exchanged among the involved agents, the actual transfer may take place through the interconnecting telemedicine hub located in the middle tier of **Figure 2**. This is just a thin synchronization layer responsible for dispatching data among agents, which can be implemented as a foundation infrastructure deployed on each agent.

Besides the reminder service, the **Figure 2** also shows some additional services whose implementation is believed to be mandatory in almost any context. Nevertheless, this list is not to be considered complete or fixed, as implementing new services simply entails writing the two matching pairs to be plugged in on each side, relying on the assumption that the synchronization layer remains completely unaffected.

Results

The architecture described in the previous section has been implemented into a platform that makes it possible to deploy services on a large number and many types of clients. This implementation addresses both short-term studies, such as clinical trials, and long-term ones, such remote follow-ups for chronic diseases, where many outpatients spread over the territory are cared for by a significantly smaller number of specialists working at a clinic. Agents are deployed on mobile devices such as smart phones or personal digital assistants to maximize the ubiquity of the service, but the utilization of desktop computers and laptops is supported as well.

In order to favor the deployment of the platform on top of different communication devices, we first modeled the unifying computational architecture of a generic remote agent depicted in **Figure 3**. The components are divided into three main categories: device-dependent components, device-independent components, and services. The first one includes software modules whose development is highly dependent on the specific architecture such as the user interface that strongly depends on the device operating system (e.g., Nokia/Symbian, Windows, Mac, Android) and the network interface that has a deep connection with the device hardware.

The center tier of Figure 3 represents the application logic, which is also device dependent, because it is strongly connected with the other blocks in this category and represents the functional core for each agent. However, this component may also host some domain-specific knowledge if an application requires any customization for a particular domain, such as a data acquisition procedure, which is highly dependent on the medical context, or some domain-specific knowledge for detecting and handling critical events directly on the agent.

Any other component shown in **Figure 3** and belonging either to the device-independent component tier or to the services tier is totally independent of the domain or the device hardware. The components represent the foundation upon which application logic relies to utilize local connectivity with personal medical instruments (e.g., blood pressure monitors, scales, glucometers), remote data synchronization with other agents and the hospital agent, as well as for tracking tasks executed by the user. For example, the Bluetooth communication module takes on the burden of establishing connections

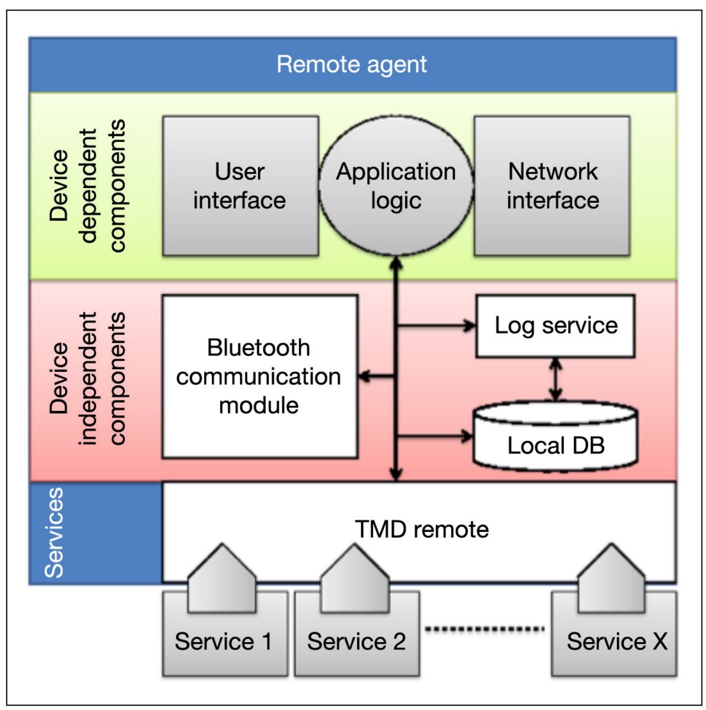

Figure 3. The communication agent computational architecture. DB, database; TMD, telemedicine.

with personal medical instruments. A local database is also available on each agent in order to store a copy of the patient EHRs generated through all the measurements, the outcomes of accomplished tasks, and other relevant application-dependent data. Health records may be manually entered by the patient through the user interface or automatically collected from local instruments, while a log service is responsible for tracking tasks and storing any information about completion statuses and outcomes into the local database. Finally, the services tier is where all service endpoints plug into an agent. Each endpoint represents one half of a service pair, which completely defines the representation format for its data. It exchanges those data with the hospital agent dispatching them through the telemedicine remote module. The telemedicine hub is then involved as the data synchronization layer using SyncML, an open standard protocol defined and maintained by the Open Mobile Alliance,[19] through the implementation provided by Funambol.[20]

In order to test the usability of the LifePhone platform, we implemented some prototypes addressing typical long-term and short-term monitoring scenarios for diabetes patients.

Remote Monitoring of Major Diabetes Complications—Long-Term Monitoring

One of the prototypes was meant for managing uremic patients who are experiencing renal failure as a major complication of diabetes and are thus undergoing peritoneal dialysis. Uremic patients fill their abdominal cavity with a suitable solution several times per day for cleaning their blood by osmosis. Therefore, it is mandatory that they keep pressure and weight under strict control because this information acts as a cue for preventing cardiac failure and avoiding overhydration or underhydration. The dynamics of body hydration is very fast, so patients are instructed to take frequent measurements, i.e., one weight and two blood pressure readings per day. A reminder service was set up on the communication agents to inform them when the next schedule was approaching. For each patient, physicians set up thresholds distinguishing normal ranges from alert zones and a compliance monitor service was also deployed on the hospital agent in order that alarms be automatically generated and sent to the communication agents of the treating staff. **Figure 4** shows the patient's kit composed of a scale, a blood pressure monitor, and a network computer or mobile phone running the communication agent. Agents were configured for automatic data acquisition because measurement devices were already equipped with Bluetooth. Patients could choose between the network computer or the mobile phone solution according to their personal preferences. A technical/usability trial was conducted on a very small scale, also including elderly patients, showing that they all felt comfortable with LifePhone and performed well.

Remote Monitoring of an Artificial Pancreas Device—Short-Term Monitoring

Presently, continuous subcutaneous insulin infusion regimens are still controlled through glucose readings taken three to seven times per day, implementing what is best known as a partial closed-loop scheme. However, advances in biotechnologies are opening the possibility of continuously monitoring blood glucose level,[21] thus anticipating a true closed-loop scheme, which has been called the artificial pancreas (AP) and whose control law replicates the process already occurring in healthy individuals.

Besides a glucose sensor and insulin pump, the AP also requires a control unit as a core component. This unit continuously processes the readings coming from the sensor and appropriately drives the pump to deliver insulin according to a suitable model of glucose absorption.[22,23] Our second prototype addresses this scenario, using LifePhone as a telemedicine platform for the remote monitoring of diabetes patients who are undergoing short-term training sessions with closed-loop therapy. The work is taking place in the context of AP@Home, a European-funded project within the Seventh Framework

Figure 4. The patient kit addressing the peritoneal dialysis implementation.

Programme, whose overall goal is to build and evaluate a complete AP solution with automated closed-loop glycemic control for diabetes patients. More specifically, the requirements called for a telemetry support, allowing specialists to monitor in real-time the patient's state during closed-loop experiments, combined with the capability of detecting potentially hazardous situations that could be promptly raised to their attention. In this case, the agent located at a patient's home is interfaced with the artificial pancreas unit (APU) that represents the actual medical device operating on the patient. The basic issue driving the design of the agents has been the complete separation between the medical device and the telemedicine platform so that the former is the only one devoted to acquiring measurements or inputting manual information by the patient. In fact, the generality and flexibility of our architecture makes no claim on the hardware on which the APU and agents run. Presently, all the available APUs happen to be running on personal computers, so agents have also been implemented on that platform, and a dedicated Internet connection will be used for ensuring real-time monitoring. Nevertheless, once APUs are regularly used for patient treatment, and possibly be ported on embedded devices, a lighter solution involving mobile devices could be adopted for logging the patient's state on a less frequent basis.

For that prototype, we enabled just the data acquisition service and the compliance monitor service. This implementation addresses a scenario where events may cause serious consequences for a patient's life if not promptly detected and corrected. The compliance monitoring service has been therefore configured to notify multiple agents so that the treating staff, the caregiver, as well as the patient himself may be advised. The settings of the APU thresholds are defined by the health care providers using the Web-based interface of the compliance monitor.

Discussion

Diabetes is the chronic disease addressed by the highest number of telemedicine applications, many of which have also been involved in clinical studies. Thus, a literature review provided us with a good starting point for assessing the state of the art in this area and understanding why almost none of them has become part of routine treatments despite a technologically sound infrastructure and improvements on the clinical conditions.[24,25] Our architecture has then been designed with the aim of reducing these issues, if not removing them altogether.

What emerged is that the impact of a telemedicine service is both clinical and organizational and that the latter issue is often underestimated.[26,27] Almost any current implementation is definitely centered on using different technologies for the collection, transmission, and storage of clinical data into the EHR and is possibly complemented with some support for exchanging messages. However, besides enforcing the availability of patient data, the traditional approach proved unable to add enough value to the treatment, as it is perceived from a physician's viewpoint. In fact, it goes directly in the opposite direction, requiring more data to be processed as physicians complain about information overload.

What these implementations seem to be missing is the ability to effectively support case management in a complex event-driven environment populated by multiple actors. A system should process data with a relatively high degree of autonomy[28] and only notify people about the occurrence of events, through customized alerts and reminders,[29] when their attention is required. This is exactly the gap we are addressing through our architecture, which has been shaped on the concept of service instead of that of a monitoring station as usual. By assembling different services on each communication device, we are able to implement agents exhibiting varying functionalities useful for capturing the needs of any role involved in the process. The present focus of our work is not addressing software agents from a strict artificial intelligence perspective, as we see each one of them just as a tailored device facilitating the interaction of its user with others. Nonetheless, given their autonomy, they collectively build up a community of cooperating agents.

The availability of multiple hardware devices is particularly useful in bringing the required functionality to different actors meeting their usability requirements. In fact, different interfaces and interaction paradigms need to be utilized to facilitate its adoption by particular user groups, such as elderly people.[30] Another great opportunity favoring the dissemination of telemedicine systems is provided by the availability on the market of several instruments able to acquire clinical data and exchange those wirelessly, partly alleviating the well-known problem of their interfacing with an ICT infrastructure.[31] Similar devices are extremely useful to speed up the data acquisition process and also remove a great source of human errors. Because wireless protocol use may vary, including infrared, Bluetooth, or even Wi-Fi connectivity, supporting a variety of devices provides the widest choice for user connection.

Our architecture considers each communication device as an agent, and thus far, it is composed only of front-end agents, which are those supporting interaction and communication with users. However, services are meant to partition a complex functionality into more manageable elements, and the modularity designed on the hardware side originally meant to cope with the capabilities of various devices can also be used to assemble applications not requiring a direct human intervention, thereby giving rise to back-end agents. This opens up the possibility of including additional services ranging from the usual decision support systems for recommending clinical actions while treating a case to more complex scenarios involving data mining useful in epidemiological studies. Additional services may also be implemented for checking the efficiency of health care providers using workflow modeling techniques such as those currently employed by the government or any other stakeholder to control the process.

Finally, this issue also represents another strength of the architecture, since it allows its utilization within the context of Serviceflow Management Systems.[32] Those tools address the need for information exchange among different health care institutions rather than just between a patient and the treating staff at a single center. Thus, our architecture could be implemented to grant the patient access to a much greater source of expertise, assembling a "virtual hospital" out of different services exposed by various centers of excellence. The most appropriate center could be contacted on the occurrence of any particular event so that each one of them might remotely contribute within the limit of their competence and expertise.

Conclusions

This article illustrates a general architecture, along with the matching LifePhone software platform, which we devised to support home monitoring in outpatients affected by chronic diseases. From a conceptual point of view, the distinguishing feature of the architecture lies in the possibility of configuring multiple services of interest within a single communication device acting as an agent and supporting a user in accomplishing his task. From a technical point of view, the LifePhone software infrastructure adopts open source standards and protocols in an effort to be portable to a broad class of mobile devices, with heterogeneous interfacing and computational capabilities with minimal effort.

According to this view, the telemedicine infrastructure has been made virtually independent from any clinical context, emphasizing scalability and modularity. The result is a highly configurable environment, which can be tailored to any specific need with minimum development efforts.

A basic set of generic services has also been identified and implemented within the platform, which has been therefore shaped as a generic one from the ground up, instead of being biased toward any particular medical specialty. Thus far, they include a telemetry service for remotely transferring data from a patient's home to the clinic responsible for overseeing him, a reminder service for acknowledging the user about important tasks to be accomplished, and a compliance monitor service, which is devoted to managing the case by interpreting any data available. Finally, the compliance monitor interacts with a messaging and alert service for notifying the target person about any relevant event using the most appropriate communication channel, such as short message services, outbound voice calls, emails, or triggering alarms on the target user interface if he has one.

The architecture and its matching implementation have been successfully used for setting up two different scenarios addressing diabetes patients on the long term as well as on the short term. On the long term, the focus is on monitoring the home treatment of patients affected by chronic renal failure and undergoing peritoneal dialysis. The application has been tested in a trial at a major public hospital located in northern Italy, proving that even old patients felt comfortable with it. On the short term, we instead proposed a telemedicine implementation useful for educating patients to the AP therapy and testing its benefits. That service will also represent the infrastructure for conducting a randomized controlled trial aimed at evaluating the effectiveness of AP as a treatment over a medium-sized patient population. The study will take place within the AP@Home project funded by the European Union.

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