Ambient Computing Research for Healthcare: Challenges, Opportunities and Experiences

Investigación en Computación Ambiental para la Salud: Retos, Oportunidades y Experiencias

Jesús Favela[1], Ana I. Martínez[1], Marcela D. Rodríguez[2] and Víctor M. González[3]
[1]favela@cicese.mx, [2]martinea@cicese.mx, CICESE, Ensenada, México
[2]marcerod@cicese.mx, UABC, Mexicali, México
[3]vmgonz@manchester.ac.uk, University of Manchester, UK

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Abstract.
Ambient computing refers to the development of physical environments enhanced through information and communication technology to better serve the needs of users. In contrast with traditional computer applications, ambient computing offers a vision in which computer support migrates from the desktop to the physical environment, thus demanding natural means of interaction, in contrast with the traditional keyboard and mouse. This approach to computing is particularly well suited for working environments characterized by local mobility, frequent activity switching, and intense collaboration, as it is often the case in healthcare. This paper provides a comprehensive overview of research conducted in Mexico for several years towards the development of an ambient computing environment in support of hospital work, the iHospital. The paper describes the research methodology used, major findings, ambient computing technology that has been designed and developed as a response to the needs identified, and results from its evaluation with potential users.
Keywords: Ambient Computing, Pervasive Healthcare, Medical Informatics

Resumen.
La computación ambiental involucra el desarrollo de ambientes físicos enriquecidos con tecnologías de información y comunicaciones para asistir a las necesidades de los usuarios. En contraste con aplicaciones computacionales tradicionales, la computación ambiental ofrece una visión en la que el apoyo computacional migra del escritorio al entorno físico, demandando con ello modos naturales de interacción, en lugar de utilizar el teclado y el ratón. Este modelo de computación es particularmente adecuado para ambientes de trabajo caracterizados por movilidad local, cambio frecuente de actividades, e intensa colaboración, como sucede comúnmente en el sector salud. Este artículo ofrece una visión del trabajo de investigación que se ha realizado en México durante varios años para desarrollar un entorno de cómputo ambiental en apoyo al trabajo hospitalario, concepto al que hemos denominado, iHospital. El artículo describe la metodología de investigación que se ha seguido, algunos de los principales resultados, tecnología de cómputo ambiental diseñada y desarrollada en respuesta a las necesidades identificadas, y resultados de su evaluación con usuarios potenciales.
Palabras clave: Computación Ambiental, Computación Ubicua en Salud, Informática Médica

1 Ambient computing

Ambient Computing (AC) refers to an environment furnished with heterogeneous computational and wireless communication devices, naturally integrated and, at the same time, invisible to the user. The development of AC demands an interdisciplinary approach, borrowing methods and techniques from computing fields, such as Ubiquitous Computing, Context-aware Computing, Human-Computer Interaction (HCI) and Artificial Intelligence (AI). Ubiquitous computing refers to an environment saturated with heterogeneous computational and wireless communication devices naturally integrated to human activity (Weiser, 1991). The environment should be aware of the user's context to provide information and services whenever users need them, in a proactive fashion and anticipating user's needs. Furthermore, the services provided by the environment have to be accessible to diverse and non-specialist users through simple and natural means of interaction, thus the importance of HCI research in the field. Finally, AC environments require advances in AI to be adaptive to users, reactive to context, and capable of learning from user's behavior in order to provide high quality services based on their preferences. Context-aware computing refers to an application's ability to adapt to changing circumstances and respond based on the context of use. A system is context-aware if it uses context to provide relevant information and/or services to the user, where relevance depends on the user's task. For example, a time-aware alarm turns a coffee-maker on, or opens the bedroom curtains when the user wakes up; or a car augmented with a GPS informs the driver the best path to a destination.

Healthcare environments, and hospitals in particular, can benefit from the use of context-aware applications (Bardram, 2006). Hospitals are technology-rich environments, whose workers experience a high level of mobility resulting in information infrastructures with artifacts distributed throughout the premises. Indeed, some elements of context-aware computing are gradually being introduced in hospitals (Bardram, 2004; Muñoz, 2003). One such example is the "Hospital Digital", build in Lagos de Moreno, Mexico by IMSS (www.imss.gob.mx/). These are working environments filled with increasingly complex technology, including computers and sensors, where patient care requires coordination and collaboration among specialists; and the working staff is highly mobile and technology savvy. The context-aware elements introduced in these environments range from wireless networks, Personal Digital Assistants (PDAs) (Chin, 2005), Radio Frequency IDentification (RFID) tags for patient tracking (O'Connor, 2006), voice-activated communication devices (Stanford, 2003), and sensors for patient monitoring (Pentland, 2004).

Hospital staff face working conditions that are substantially different from those of office workers, for which traditional desktop computers were developed (Bossen, 2002; Bardram and Bossen, 2005). Hospitals are dynamic and intensive work environments whose staff perform multiple activities and cope with frequent contingencies that require them to constantly adjust and readjust their actions (Bardram, 2003). In addition, hospital workers are highly mobile and experience a high degree of collaboration and coordination with colleagues. The activities of most hospital workers, clearly, are not tied to a desktop or a specific location because they need to move to locate colleagues, take care of patients, and access information and other resources distributed in space (Bardram, 2003; Muñoz, 2003). This phenomenon, identified as local mobility (Bellotti, 1996), requires the user to change his "work place" constantly and even suddenly. Besides, the specialized nature of medical work makes the treatment and care of patients an inherently collaborative effort among specialized medical workers who have to be in constant communication with each other to be able to perform their activities.

These working conditions call for a new computing paradigm for hospital work, one that supports collaboration and coordination, mobility, seamless interaction with heterogeneous devices, and frequent task switching. This paper describes research efforts we have conducted in the area of ambient computing in support of hospital work. We first describe the research methodology that has been followed, the workplace studies we have conducted in hospitals, and provide examples of ambient computing technologies that were developed guided by the results of these studies.

2 An Approach to Ambient Computing Research

For the last six years, we have conducted a series of workplace studies in a mid-size public hospital in Ensenada, Mexico, aimed at consolidating a conceptual understanding of hospital workers' interactive behaviors during their everyday practices, to guide the design of ambient computing technologies.

These studies are part of the research methodology we have followed, which is depicted in Figure 1, and described next[1]. The components of this methodology emerged from consolidating techniques from the Human-Computer Interaction (HCI) literature, including workplace and ethnographic studies of work practices (Hutchins, 1996; Luff et al. 2000; Orr 1996), scenario-based design (Carroll, 2000), conceptual modeling and prototyping (Beyer, and Holtzblatt, 1998; Preece, et al, 2002) and user evaluation and usability testing (Rubin, 1994). Each approach contributes to understand and evaluate the relevance of particular aspects for developing ambient computing technology. Together, they constitute a pathway taking us from the assessment of the context to the testing of systems and tools designed to serve healthcare workers. In contrast with typical software engineering development cycles (e.g. those described in Sommerville 2004), our methodology is research oriented and considers

[1] A first version of our methodology is presented in (Gonzalez et al. 2004).

these systems as vehicles through which we can understand the opportunities of ambient computing technologies and its implications at the personal, or group level.

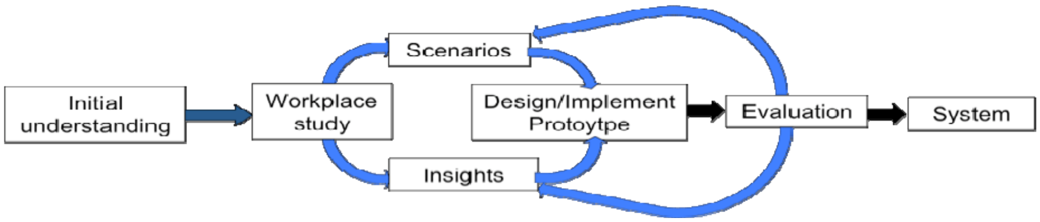


Fig. 1. Methodology used in the development and evaluation of ambient computing technology for healthcare

2.1 Initial Understanding

Our efforts begin with an initial understanding of the practices we want to support, these come from previous experience in healthcare process re-engineering, which included the analysis of written procedures, formats and current practices (Kettinger, et al., 1997), and a preliminary vision of the nature of the technology we planned to develop: ambient computing support for hospital processes.

2.2 Workplace Study

With the aim of acquiring a robust understanding of the essential contextual elements that support the management of information in a hospital setting we have conducted a series of workplace studies (Hutchins, 1996; Luff et al. 2000; Orr 1996). We use qualitative methodologies to gain a more complete understanding – compared with that provided by standard requirements gathering techniques – of how routine and non-routine work is performed in a daily basis. Using participant observation and interviews to study several areas of the hospital, we spent more than 200 hours observing nurses, physicians, and lab staff, while doing their work. We moved around the hospital by ourselves or following a physician or a nurse (Figure 2). In this way we conducted many informal interviews that let us to become familiar with the setting, people, and their practices.

Together, observations and interviews have been used to construct an understanding of the effects of contextual elements on managing information in the hospital. We analyzed the transcripts of the interviews and notes and produced a grounded representation of the work in order to synthesize the particular characteristics that ambient computing technologies ought to support. The workplace study provided us with two important inputs to our design: scenarios of use and insights into work practices.

Fig. 2. Hospital workers during one of the observation days. (a) A head nurse and medical intern consulting a medical note and (b) Medical interns in a ward round discussing a clinical case and (c) Medical interns transcribing medical notes gathered during their rounds

A quantitative analysis was conducted to estimate the time hospital workers spend in different activities; the distance they move, the places they move to and the reason for moving there; the people they collaborate most often with and the artifacts they use in support of their work.

The results obtained from the analysis enabled us to understand the work practices and typical interactions experienced by hospital staff (from a qualitative perspective), and to quantify the time hospital staff invested in those behaviors (from a quantitative perspective). Furthermore, our analysis let us measure the mobility experienced by hospital workers and the frequency of the interactions carried out with artifacts and colleagues. Based on this data, we were able to characterize the hospital activities to establish a ground base for the design of mobile and pervasive technology. In the next section, we discuss these results and their implications.

2.3 Scenarios of Use

We use scenarios to frame our understanding of hospital's work practices and also to project our vision of how their work could be augmented with context-aware tools. We have used a scenario-based approach (Carroll, 2000) to frame our findings from the study into specific vignettes that offer a new vision of how context aware tools can operate into the current work practices. Scenarios are a convenient approach to evaluate novel technologies at the early stages of their development or even when analyzing the actual adoption by users (Ikonen, 2002). A brief example of one of these scenarios is the following:

Rita, a doctor in a local hospital, makes her final round and notices that a patient is not responding well to her medication. Rita wishes to leave a note to the doctor who will be reviewing the patient in the afternoon shift. She doesn't know who that will be, so she writes a message to the first doctor to check the patient after her and attaches it to the clipboard containing the patient charts.

2.4 Insights and Study Findings

We have conducted extensive qualitative analysis of the data collected from the case studies. The particular qualitative approach we have followed was inspired by the techniques to derive grounded theory originally proposed by Strauss and Corbin (1998). These techniques have been widely used in a variety of research studies focused on the study of information systems usage, distributed collaboration, and medical informatics. For our particular case, the qualitative technique of analysis has involved continuous sense making of the information collected including interview transcripts, personal notes and documents.

From the studies we identified the characteristics that ambient computing technologies should support (Muñoz, 2003). In particular, we identified that collaboration in a hospital is highly based on a set of contextual elements such as: (1) the location of people and devices, (2) the timing of messages to be delivered, (3) the role-oriented nature of the work and (4) the artifact-mediated nature of information gathering. For instance, access to a patient's medical record is most relevant when a doctor or nurse is with that patient; likewise, different slightly from the scenario presented before, a doctor might want to leave a message that describes recommendations for treatment to the nurse on the next shift, and he might not know a-priori who that nurse will be; or a doctor might want to display the patient's lab analysis results in the closest public display as soon as they become available.

2.5 Design and Implementation of a Prototype

Scenarios and findings guided the design that led into prototypes with different degrees of functionality (Beyer, and Holtzblatt, 1998; Preece, et al, 2002). For instance, we extended the Instant Messaging paradigm to support what we refer to as context-aware communication, which enables users to specify a set of circumstances that need to apply for a message to be delivered. For example, the sender can indicate that the message will be sent when the recipient enters the emergency room; or for a message is to be sent to the last person to leave the laboratory when the air conditioning is on.

To illustrate the use of the context-aware messaging system we revisit the scenario presented before. As Rita, the physician in turn checks her last patient; she decides to send a message to the doctor who will be reviewing the patient in the afternoon shift. She turns to her PDA showing the Context-aware client, which lists the staff and devices available in the hospital, to send a message to the first doctor to check the patient during the next shift. As illustrated in Figure 3a, this client is able not only to notify the status of other users, but also to show resources available in the vicinity, such as a printer, and their status as well as the services they can provide to the user. In addition to the information provided by an instant messaging system, the Context-aware Client also shows the location of users and devices if known. This information is shown in parenthesis after the user's name (Figure 3a) or in a map (Figure 3b).

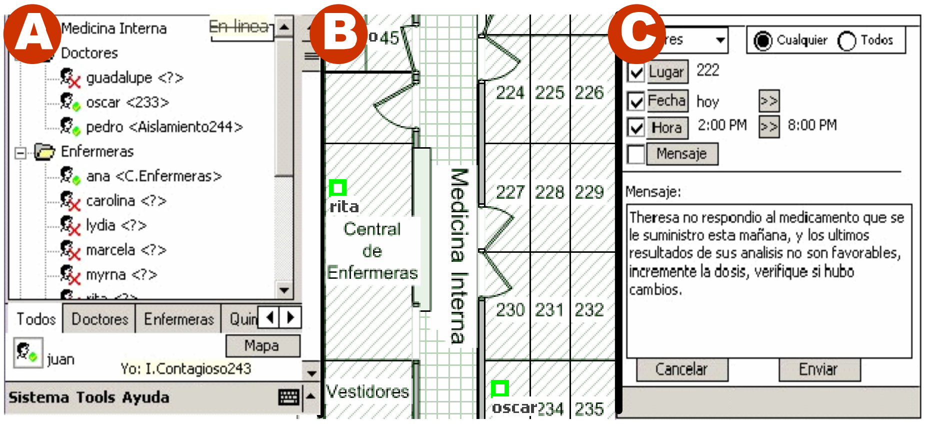


Fig. 3. The Context-aware System provides users with awareness information of other people and devices (a, b), and lets them exchange messages that depend on context for their delivery (c)

When a context-aware message is created, the sender specifies the criteria that need to be met for the message to be delivered. Figure 3c shows the form used by Rita to write the message and specify the context for its delivery. Rita writes the message and specifies that it should be sent to any doctor to be in Room 226, after 2pm, today. Additional details on the system's functionality can be consulted in (Muñoz, 2003).

2.6 Preliminary Evaluation

A preliminary evaluation of novel technology is important before actual deployment and investing on the required infrastructure, to evaluate the system's core characteristics, the staff's intention to use the system, and their perception of system utility and ease of use (Preece et al. 2002; Rubin, 1994). According to the Technology Acceptance Model (TAM) (Davis, 1989), these aspects are fundamental determinants of system use.

For the case of the application described before, the participants of the evaluations were the staff involved in the respective processes; they validated scenarios and provided us with additional insights and opportunities for applying our technology (Muñoz, 2003). The results of the TAM questionnaires mostly showed that a high percentage of the participants would use the systems; additionally, showed that many believe that using the systems would enhance their job performance -a high degree of perceived usefulness- and a high percentage perceived the systems to be easy to use.

From the results of the preliminary evaluation we have modified the systems and improved their robustness. The evaluation also motivated the hospital's administration to support conducting a pilot study.

3 Towards an understanding of hospital work

This section presents some of the main results obtained from our studies, showing the mobile nature of hospital work, the frequency and percentage of the time invested in activities performed by hospital workers, and the interactions with artifacts and colleagues. As will be shown in Section 4, these findings have been used to guide the design of ambient computing technology for hospital work.

3.1 Characterizing and quantifying activities performed by hospital workers

Here we present the results of our qualitative and quantitative analysis to understand the medical behaviors experienced by those individuals observed (Morán, 2007).

3.1.1 Activities performed by hospital workers

From our qualitative analysis, basic fundamental activities emerged. These are the meaningful consistent patterns of activity or behaviors that could be extracted from the data collected through the qualitative analysis. We observed that these behaviors could take place either at a “base location” (this is the place where the subjects spend most of their time) or “on the move” (while away from it). For nurses, the base locations were either the nurses’ pavilion or the nurses’ office. For medical interns and physicians it referred to a common office shared with personnel of the department. These fundamental activities are the following: Information management; Coordination; Clinical case assessment; Patient care; Tracking people medical equipment and documents; Patient census; Training and certification.

3.1.2 Hospital workers' activities

We measured the time hospital workers spent in the activities established in the qualitative analysis (see Table 1). Most of the time is spent in information management (20.86%), followed by clinical case assessment (19.38%), coordination (16.54%), personal activities (15.69%) and patient care (15.63%). Upfront, it is clear that an important part of the work of those observed is focused on activities that have a secondary goal of caring for patients such as information management, coordination, tracking, and preparing the patient census. In fact, the time nurses and medical interns spend in these activities surpasses the time they invest providing clinical care. This is in contrast with physicians, who spend more time evaluating clinical cases and with patients. We observed that nurses and medical interns spend considerable time “*setting up*” the environment, for physicians to focus on their main goal: providing clinical care.

Table 1. Time hospital workers spent performing different activities

Activity (time per day per subject)	Average total time	% of the entire day
Information management	1:22:29	20.86
Clinical case assessment	1:12:05	19.38
Coordination	1:03:23	16.54
Personal activities	1:02:14	15.69
Patient care	1:04:15	15.63
Preparation	0:28:27	6.67
Tracking	0:11:15	2.90
Training and certification	0:09:22	2.32
Unknown	0:00:02	0.01
All	**6:33:34**	**100.00**

Hospital staff spends a considerable amount of time managing information during their work shift; therefore, we decided to look closer at the different tasks included in this classification. *Information capture* represents 13.43% of the information management activities. Information might need to be captured to create or maintain artifacts that serve as medical documentation (e.g. a medical record of a patient). On the other hand, information can be captured to support coordination between hospital workers (e.g. a table listing schedules for different nurses). Another significant task is *monitoring information status* which takes on average 4.95% of the information management activities. Hospital staff monitors information to be aware of the status of requested medical tests, clinical histories or medical notes. *Gathering information* represents 2.74% of the time spent on information management activities. Hospital staff performs this task to engage in the compilation or search of information artifacts. We observed that the information searched might be in paper or digital form. *Information consultation* takes on average 1.29% of the time. Information might need to be consulted to support decision-making, synchronize information or elaborate reports. Finally, *formalizing information* represents 0.27% of the information management activities. This task was carried out when individuals formalized in documents medical information that was originally captured on a piece of paper or in their notebook, for instance, during ward rounds.

3.2 Mobile nature of work

We first identified those *operation centers,* within the information space, that were visited by the subjects during the period of observation. We called operation centers to the physical places where hospital workers conducted their work, places such as laboratories, hospital departments, nurse's areas, trauma areas, and so forth. We classified them into 5 operation centers. We found that each subject moved around an average of 15.5 (s.d. 5.5) different operation centers per day during the time of observation.

A second analysis was directed towards revealing the weight that mobility plays in the work practices of those observed. We found that individuals spent, on average, 59.92% of their time in their base location while the rest is spent at other operation centers (40.08%). Upfront it is clear that an important part of the work of those observed is conducted outside their bases. Nurses, physicians, and medical interns have to care for patients in different rooms and consult information in other areas. Also, we found out that medical interns and physicians spend almost 10% of their time in the hallway. We observed that when those subjects were in the hallway, other staff often contacted them to ask for specific information (laboratory results, administrative forms, reference material, etc.) or issues related to patient assessment. Also, the physicians and medical interns choose the hallway to discuss the health condition of a patient with colleagues or relatives. Thus, the hallway is used as an *"availability space"* where many discussions and information exchanges take place.

An additional analysis of our data was focused on the distance covered by our subjects during their work shift. This information was used to complement our understanding of their mobility. By measuring and computing the distance walked among operation centers, we found that on average our subjects covered around one (1) kilometer during their work shifts (mean 1076 meters - s.d. 593 meters). Looking at the individuals' episodes of displacement, we found that every time a subject had to move from one place to another (except for short distance within the same operation center), on average the subject moves a considerable distance (18.75 meters – s.d. 13.42 meters). This is an indication of the high mobility experienced by hospital staff while conducting their work.

3.3 Interactions with people and artifacts

We conducted further analysis to determine the percentage of time that people interact with their colleagues. Both medical interns and nurses spend most of their time interacting with subjects of the same role. For example, medical interns spend 49% of their work shift interacting with other medical interns. Similarly, head nurses spend 24% of their time interacting with other nurses. In contrast, physicians spend 53% of their work shift interacting with medical interns.

We also measured the amount of time that subjects spend interacting with information artifacts. The artifact most often used is the medical record, used on average in 22% of the subjects' work shift. As we expected, the subjects that use this artifact most of the time are the physicians the medical interns. In contrast, nurses spent 24% of their work shift writing or consulting a nurse sheet. Medical interns are the ones who used computer equipment the most (17%), while nurses seldom used them (0.6% of their day, for an average of less than 3 minutes a day).

4 The iHospital: The hospital as a smart environment

The concept of the iHospital is that of a healthcare facility that seamlessly integrates a variety of information technology to assist the activities of hospital staff. It is based on ambient computing technology in response to the characteristics of this working environment, which include: high mobility, constant activity switching, the need to coordinate activities with colleagues, and the abundance of information. These are circumstances that are rather different from those of traditional office workplaces for which most information technology has been developed, and demands the use of alternative and novel solutions.

The hospital as a smart environment (iHospital) is a vision of a highly interactive workplace, where hospital staff can access relevant medical information trough a variety of heterogeneous devices, and can collaborate with colleagues taking into account contextual information. The iHospital provides ubiquitous communication infrastructure, providing access to relevant information anywhere and anytime. For a hospital a key information component is the medical record, thus facilities should be provided to facilitate access to it and means to record information on it. Furthermore, sensing devices are used to monitor and derive relevant contextual information, such as the location of people and artifacts, the activities being conducted and the availability of hospital staff with which one needs to interact. This information can be visualized on different devices, such as smarphones with limited screen size and performance; large screens that can be used to support collaborative medical diagnosis while visualizing detailed medical images, and even ambient displays used to provide subtle peripheral information to busy hospital workers. Towards the implementation of this vision, we have developed several components, which provide support for the following functionality:

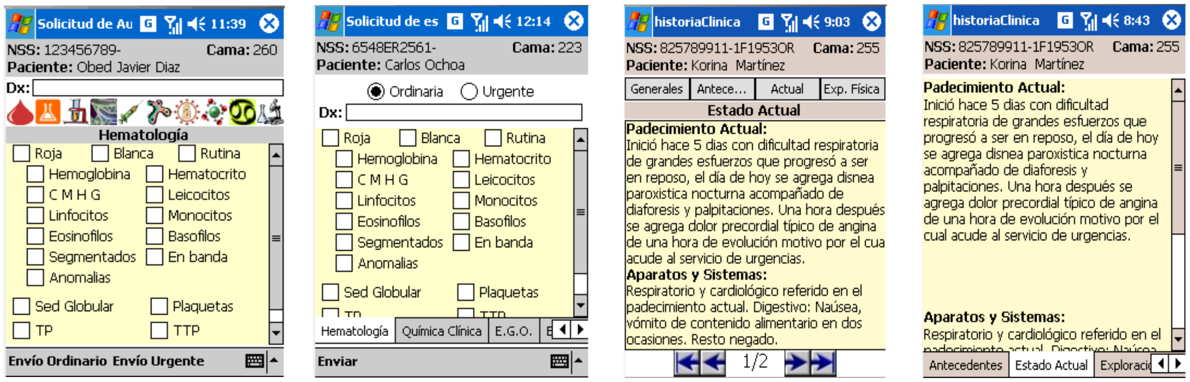
4.1 Providing awareness of people and artifacts

In a hospital, artifacts and people are distributed in space or time. Hence, hospital workers must navigate hospital premises to gather the information they need to conduct their work. Gathering information is a necessary but time consuming task. Consequently, the iHospital, aims to reduce the time hospital workers spend searching and gathering information, provides the means for hospital workers to become aware of the presence, location and status of artifacts and people (Muñoz 2003). Physicians and nurses carry a handheld computer that estimates their location, provides them with information relevant to their location, and allows them to fill requests and communicate with other members of the staff (Rodríguez 2004). The context-aware client provides access to the Hospital Information System which includes support for the Hospital Electronic Medical Record (HEMR).

4.2 Supporting the mobile Hospital Electronic Medical Record

Hospital staff is on the move continuously, and the need to access the patients' records for decision making can emerge at any time during their working shift. Therefore the use of mobile devices such as PDAs to access the HEMR at any moment is essential to provide appropriate care. For instance, if a physician is checking a patient on the hospital bed and finds a symptom of a hospital-acquired infection, s/he at that point fill in a lab form request to verify the diagnosis and act according to the findings quickly.

The design and use of a HEMR in handheld devices, requires dealing with usability problems that come with the use of these devices, using techniques that facilitate information input, navigability and display. Therefore we developed the applications that conform the HEMR using a mixed of different techniques for the input, navigability and display of medical information; within these we used checkboxes, combo boxes, buttons, tab bars, scrollbars, fisheye, zoom, paging buttons, etc. For instance we implemented the laboratory request form with buttons and scrollbar (Figure 4a), and with tab bars, checkboxes and scrollbar (Figure 4b) and the clinical record with tab bars and paging buttons (Figure 4c) and scrollbar (Figure 4c).



(a) **(b)** **(c)** **(d)**

Fig. 4. Hospital Medical Record applications for PDAs designed with different techniques for the input, display and navigability of the patient's clinical information; laboratory request form implemented (a) with buttons and scrollbar, and (b) with tab bars, checkboxes and scrollbar; clinical record implemented with tab bars and (c) paging buttons, (d) and scrollbar

We conducted a usability test of the different applications, with the variety of designs, with physicians, medical residents and interns, to determine which techniques were most appropriate for the navigability, display and input of each application of the patient's electronic medical record in a PDA. The results indicated a mixed selection of techniques that were chosen according to the activity application in used; for instance scrollbars were preferred to paging buttons that shows the information formatted as pages.

4.3 Providing hospital tools for supporting mobile Clinical Decision Making

Decisions in a hospital setting are complicated, due to the need to analyze, not only a set of signs and symptoms, but human beings; therefore it is important to take into account and analyze all possible relevant alternatives. To make correct and timely decisions in a hospital context requires information related to the medical staff, the medical area, medical resources and technological support.

Clinical Decision Support Systems (CDSS) provide clinical knowledge and information related with a patient, filtered in an intelligent form and presented in the appropriated moment to support adequate patient care (Osheroff et. al., 2004); thus, providing these kinds of tools in a hospital environment could be very useful as physicians have to make clinical decisions at any time, furthermore they are continuously on the move, therefore providing the tools in handheld devices such as PDAs could facilitate decision making at the appropriate moment.

We developed a mobile CDSS (Figure 5a) which contains a combination of quantitative (Figure 5b) and qualitative (Figure 5c) techniques, useful to provide alternative decisions according with different criteria of the patient clinical information. The system provides access to the information per patient (Figure 5a) where a physician can access the HEMR and from there the CDSS tools, where relevant patient clinical information is introduced for the tools to provide information on the possibilities of different alternatives concerning the patient health and evaluation of the different health risks, supporting in this way the physician final clinical decision for that patient treatment.

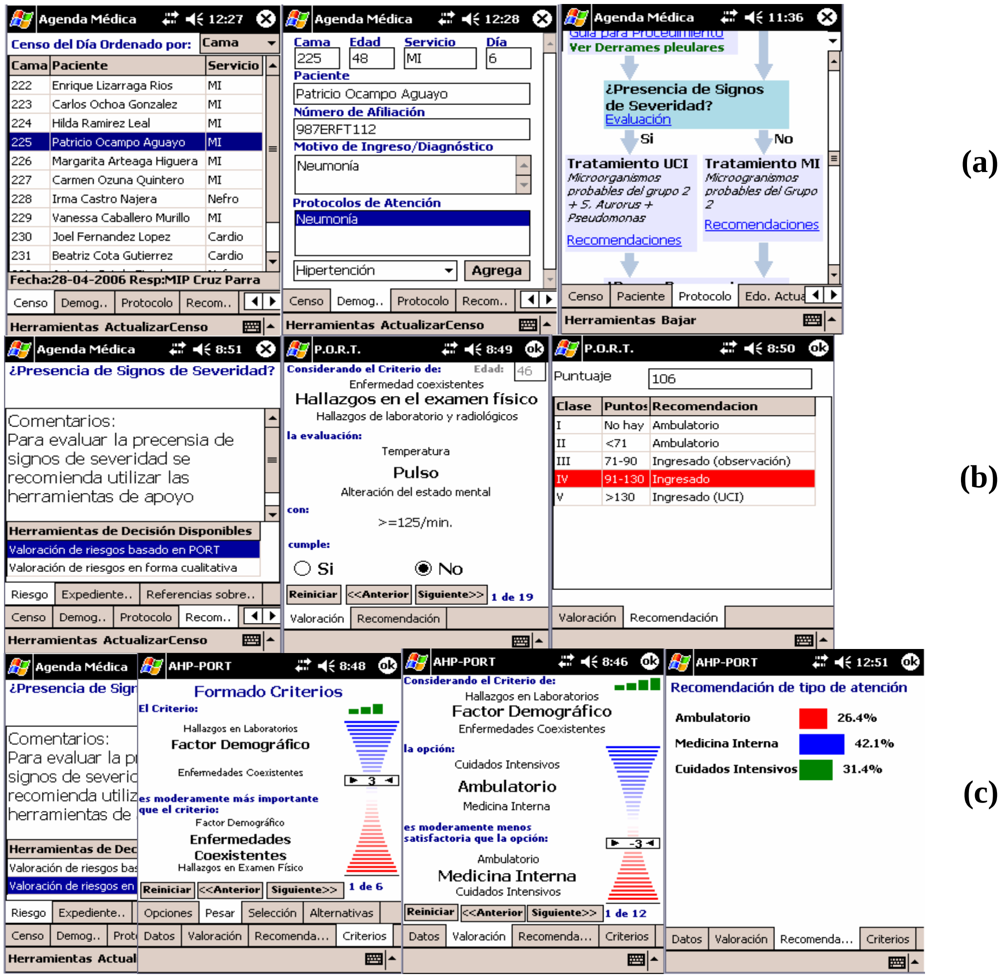


Fig. 5. Mobile Clinical Decision Support System which provides support for (a) case analysis through (b) quantitative and (c) qualitative techniques, to analyze the different alternatives concerning the patient health as support for making clinical decisions

A qualitative evaluation was performed with medical interns and physicians. The response in general was positive, especially from the medical interns who saw the mobile CDSS as support not only for decision-making, but also to train interns with clinical cases.

4.4 Supporting collaboration through context-aware communication and the seamless interaction among heterogeneous devices

Hospital staff can send messages depending on environmental conditions. As an example, a physician can send a message that will be delivered to the doctor responsible for a patient in the next shift when laboratory results are ready. The sender does not need to know a-priori the identity of the doctor that will be attending the patient nor the time when the laboratory results will become available. In addition, hospital staff can transfer information from public spaces to personal devices, share information between heterogeneous devices, remotely monitor other computers, and share handheld applications (Favela, 2004). For instance, two colleagues carrying their PDAs and discussing a clinical case using the public display could seamlessly transfer information between their personal information space (PDA) and the shared space (public display) (Figure 6).

Fig. 6. Two physicians discuss a clinical case, one manipulates information directly with a public display, while a colleague remotely interacts with the display from his PDA

We evaluated this functionality with 11 hospital workers. We asked them what media they considered to be the most appropriate to consult the patient's medical record 8 of them (61%) favored a PDAs and 7 (53%) public displays. Only two respondents marked personal computers as their preferred option and none of them selected the current paper versions. Answers do not sum 100% since subjects were allowed to mark more than one option. Responses changed slightly when asked about laboratory results, including X-rays. In this case public displays were the preferred media of 9 people (69%) and 7 of them mentioned PDAs (53%). Two people selected personal computers and two more paper versions. Clearly, physicians are attracted to the idea of having computerized access to patient records and favor the mobility offered by PDAs for clinical records, and large displays for lab results because of the limited screen size of handhelds. Yet, it seems that the need to share information with other people favored large displays over traditional personal computers.

4.5 Using context to adapt and personalize information

To provide relevant information to users, the iHospital takes into account contextual information, such as the user's identity, role, location, time, and status of information (e.g. availability of laboratory results). Thus, when a physician, carrying a PDA, is near a patient, the system offers to display the clinical record of that patient. Contextual information such as identity or role is also taken into account to adapt and personalize the information presented to the user. Thus, when a physician approaches a public display, it shows only the physician's patients, personnel calendar, messages, and the location of others with whom he may require to interact.

To achieve this he has proposed new approaches to location and activity estimation. To estimate user location we use a backpropagation neural network trained to map radiofrequency signals from access points to the mobile devices. Our contribution lies in the use of information from previous estimates during the execution of the neural network, but neighborhood during training (Castro, 2007). This approach results in an average precision accuracy of 1.3m, a significant improvement from the 2m average error obtained when no neighborhood information is considered.

Activity estimation is a mucho more complex task, but if reliably estimated, can be of great use for the design of services that adapt to the user's task-at-hand. To estimate hospital activities we have proposed a parallel layered hidden Markov model that uses from contextual information such as the people involved in the activity and the artifacts being used. We trained the model and evaluated it using the data captured from our case study. With this approach activities were correctly estimated 92 percent of the time (Sanchez, 2008). These results can also be used to infer a person's availability. For example, when hospital workers are involved in clinical case assessment, patient care, classes and certification, or even preparation, they generally don't want to be interrupted. We repeatedly observed that when a physician was involved in a discussion, medical workers, especially interns, would wait until the discussion was over before approaching them.

4.6 Supporting the nature of multitasking

Medical workers need to cope with multiple activities, which are often fragmented by interruptions, and which require them to gather and consult a great amount of information resources (Moran, 2007). Thus, an ambient computing environment must provide users with mechanisms to easily manage their activities and their associated resources. Most of the medical intern's activities are centered on their patients and their courses, which can be considered their main working spheres. These working spheres are not just their own, they are often shared, as is the case of a patient whose care is the responsibility of the intern, but also of the attending physician and responsible nurse. In addition, the responsibility is transferred to other interns as they change shifts. When the intern returns the next day, she needs to get updated on the current state and main events related to the patients for which she is responsible.

To assist mobile users in the management of their multiple activities and collaboration, the iHospital allows hospital staff to easily manage their activities and their associated resources by helping to preserve and recover the necessary context when switching between them (González 2004). Using the mobileSJ (Camacho, 2008), the user can define e-spheres for each of his activities and associate to them, information resources, contacts relevant to the activity, emails related to the activity and pending issues (Figure 7). When a user switches between spheres, each sphere is enabled to quickly gather and retrieve its own workspace state (windows positions, status and overlay order) and context information like open documents or idle time, in a silent manner. In addition, mobileSJ allows sharing activities and resources, as well as, communicating with colleagues through either SMS messages or phone calls.

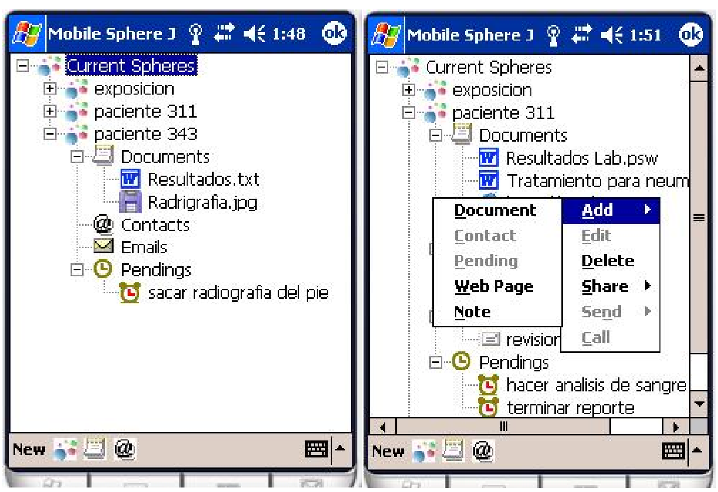


Fig. 7. Interface of the mobileSJ. Different types of resources, such as documents, contacts and pending tasks can be associated to working spheres and then manipulated from the application

We conducted a usability test with sixteen participants and a focus group with three medical interns with the purpose of evaluating the mobileSJ application and exploring its potential to support their activities. We aimed to test and improve our design by focusing on the way medical interns conceptualize their activities and the challenges around managing multiple activities. The results from the analysis of the session indicate that the activities conceptualized by medical interns can be adequately supported by the current implementation of mobileSJ. We found that written activities by medical interns match with the previous scenarios identified to guide the design of actual implementation of mobileSJ; therefore, theses activities can be technologically supported with this tool.

4.7 Integrating the physical and digital domain

Even with the introduction of computer technology, paper-based artifacts remain ubiquitous in hospital settings. The need to manually transfer and update information from the physical to the digital realm becomes a daily practice among hospital staff, which, although usually well managed, at times becomes a source for errors and inconsistencies. Estimates indicated that up to 98000 people die in the US as a result of medical errors per year (Kohn, 1999). Furthermore, the storage of information in paper, results on clear inefficiencies, as information cannot be retrieved promptly whenever and by whoever might need it. Advantages of automation are clear, however although the use of portable computers and personal digital assistants (PDAs) could be a partial solution, it is clear that much is lost when paper affordances are left out. Rather than replacing paper, our aim is to use pervasive computing technology to seamlessly integrate paper into physical-digital hospital information systems.

We have developed an augmented patient chart system, based on Anoto™ technology (www.anoto.com), that preserves the use of paper and allows capturing information directly to the digital system through the use of a digital pen (Zamarripa, 2007)). The solution maintains the essence of the original patient chart and introduces features that make it richer by providing up to date information and more powerful graphical presentations. The system was designed to facilitate its integration to the rest of information systems operating in a typical hospital (e.g. Electronic Patient Record, Messaging systems, Pharmacy Order Systems, etc). Figure 8 shows the format of the patient chart system. The solution replaces manually generated graphs of patient's vital signs (cardiac pulse, internal and external temperature) with a set of widgets to annotate accurate values used to plot graphs every time a new patient chart is created. The system allows the free annotation of data such as medications that are validated when these are transferred to the hospital information systems. It also provides ways to annotate messages to co-workers and transfer them electronically. By combining widgets with pre-defined options and free annotations the system optimizes data capture without the need of explicit character recognition.

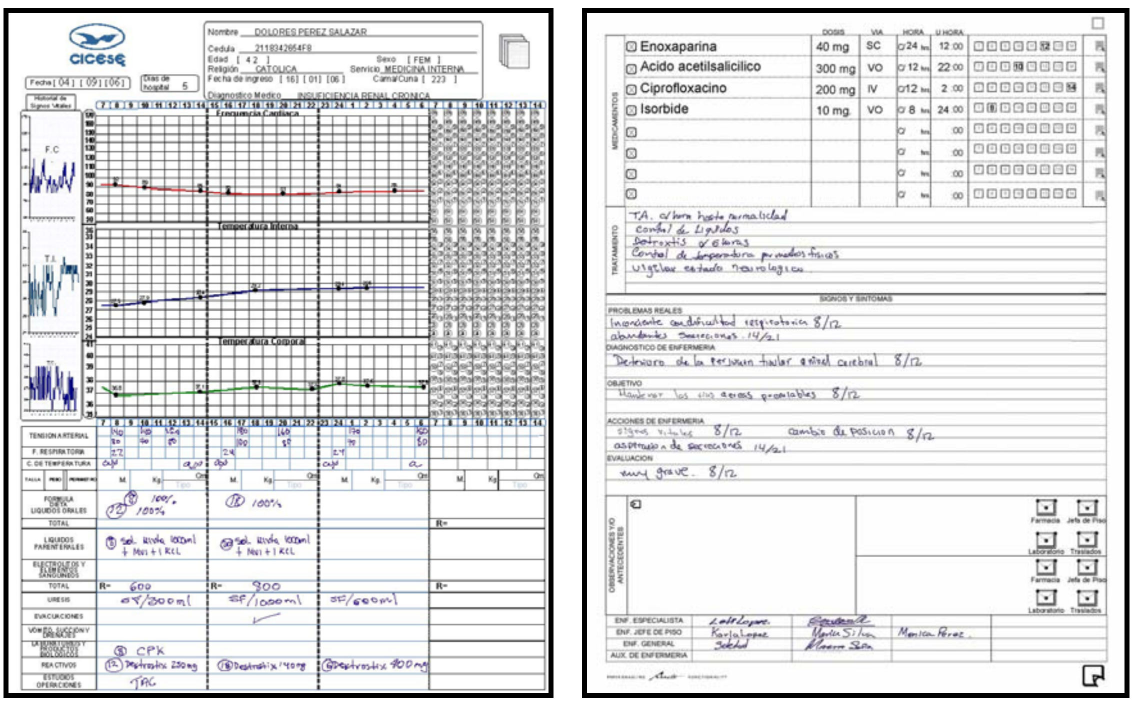


Fig. 8. The designed physical-digital patient chart (front and rear). The form has been optimized for clarity and to facilitate the digital capture of information

The system was evaluated by 22 nurse students (Figure 9). The nurse students were familiar with traditional patient charts because they have to spend practical hours at the local hospital as part of their education. After an initial training, the participants were asked to complete a set of representative tasks using both the traditional patient chart and the new version of it. At the end of the evaluation, participants completed questionnaires based on TAM that served to explore their perspectives with regards to the adoption of our solution.

The results of the evaluation indicate a significant reduction in the number of errors while reading information ($p<0.001$), a significant increment on the accuracy while annotating data ($p<0.05$), as well as trend towards less time spent while annotating data on the digital paper ($p<0.5$) (Zamarripa, 2007). Furthermore, the perceptions of participants with regards to the augmented patient chart’s usefulness are very encouraging: they recognize the advantages of the solution, but more important, the new interface does not appear to be either challenging or fundamentally modifying the essence of what is done with the artifact.

Fig. 9. A nurse uses the digital nurse chart during a usability evaluation. Nurses were asked to perform several tasks with both the traditional form and the new form designed for digital paper

4.8 Monitoring patients using ambient displays

Nurses need to constantly monitor the status of patients in order to assess their condition, assist them and/or notify physicians or specialists. Given their work load, it is not rare for them to miss important events, such as a catheter being disconnected due to the patient movement or the need to change a urine bag that has been filled. Pervasive technologies by being able to continuously monitor patients could provide awareness of the patients’ health condition. This awareness must be subtle, expressive and unobtrusive without interfering on the nurse’s focal activity. One way to overcome such difficulties is to develop ambient displays that could be embedded into the environment to provide a getaway for that information that could be displayed by objects already placed in the physical space instead of traditional computer displays (Mankoff, 2003). Objects already known and used by hospital workers could be augmented with pervasive sensors making them capable of extending their capabilities beyond its primary role while still constituting a part of the user’s environment.

We have explored the use of ambient displays to adequately monitor patient’s health status and promptly and opportunistically notify hospital workers of those changes. We designed and developed an ambient display in the form of a flower vase that notifies nurses the urine output of patients and the status of their urine bag (Segura, 2008).

The flower vase is an ambient display that notifies nurses the urine output of patients and the status of their urine bag (Figure 10) (Tentori, 2008). The display is a wooden box containing twenty-four artificial flowers: twelve emergency flowers and twelve situation flowers. The flowers are composed of a two-layered felt that enclose pistils covered with insulating tape. In each pistil a red or yellow led is embedded. The emergency flowers have stems with an embedded yellow light in their pistils (Figure 10a). All emergency flowers blink whenever an event or an emergency occurs with a urine bag wore by a patient –if a urine bag is full. In contrast, situation flowers are flowers without stems with a red light embedded in their pistils. This situation flowers are arranged in a matrix to represent the location of the patients in the area. The columns in the matrix represent rooms and the rows represent patient' beds (Figure 10b) –each room has three beds for patients. This arrangement allows nurses to quickly discover the bed where a patient is located. Situation flowers turn on whenever a nurse approaches the flower vase or if the emergency flowers are blinking. While emergency flowers are blinking a situation flower turns on, indicating to a nurse the location of the patient related to that event. If the emergency flowers are not blinking and a nurse approaches the vase, the situation flowers personalize their color by turning on only those flowers that represent the patients assigned to that nurse and for which an event has been associated.

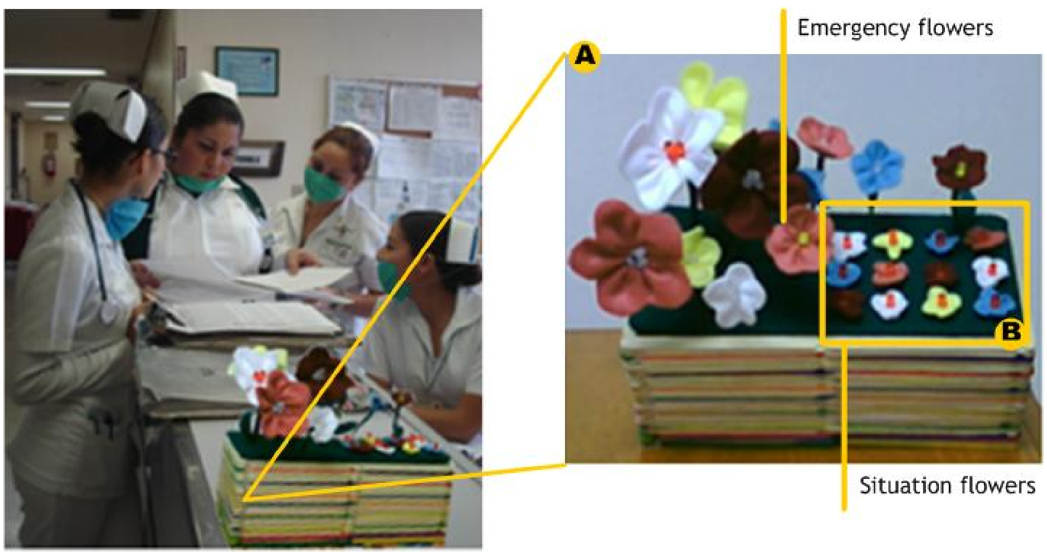


Fig. 10. The flower vase placed in the nurse pavilion. (a) The flowers that notify of emergency events (b) The flowers that personalized their color based on the nurse's presence

5 Conclusions and future work

Current trends in information and communication technologies are making feasible the development of physical environments saturated with computing infrastructure with which users can interact through natural interfaces. As we have discussed, hospitals are promising environments for the deployment of such technology given the nature and importance of the work conducted in such settings. In addition, improving working conditions in hospitals can have significant economic and social implications. To this end, we have advanced the vision of the iHospital, aimed at augmenting these work settings through ambient computing technology.

We have conducted workplace studies in a public hospital, from which design insights and scenarios have been derived in order to guide the design and development of an AC tools. These include: context-aware communication services, the seamless integration of heterogeneous devices, services for the management of multiple activities, and the integration of physical and digital artifacts, among others.

One of our original objectives when we began this line of research, was to build a “living laboratory”, that is, an actual working environment were we could gradually introduce ambient computing technologies and evaluate them. We have achieved this only to a small extent. The deployment of some of the infrastructure and technologies in the hospital has proven to be more complicated than expected and somewhat beyond our research objectives. Nevertheless, we have found the application domain to be very fruitful for inspiring the development of novel technologies. This is particularly interesting for the field of ambient computing, given that the area has been at times criticized for proposing technologies that offer limited utility and high deployment costs. Hospitals however, already have considerable technological infrastructure and even small improvements in information access or in optimizing the busy schedule of hospital staff can have significant impact in the quality and costs of care.

We are currently working on a new healthcare environment, namely, a nursing home for elders with Age Related Cognitive Decline (ARCD). We are exploring how ambient computing could be used to safely and adequately monitor elder’s Activities of Daily Living (ADLs). This in order to guide the intelligent environment how to adapt its behavior by facilitating the natural execution of such activities, as well as to notify caregivers of relevant behaviors, towards the assessment and assistance of people with ARCD. Such technology could help improve the quality of life of elders that suffer this condition and assist the nursing staff and family members who face the burden of their care.

Research in medical informatics in general, and in ambient computing for healthcare in particular, is relatively new in Mexico. There are ample opportunities to advance this field as the complexity of healthcare offers significant opportunities for novel information technologies. Research in this field not only can provide important social and economic benefits, but if provides researchers with interesting challenges to advance the field of computing.

The development of such an intelligent environment requires of advances in several fields of computer science, such as, software engineering, distributed systems, artificial intelligence, embedded systems, computer networking, and human-computer interaction. Thus, research in ambient computing, and especially for an application as important as healthcare, can be a good catalyst for the integration of diverse research efforts from the computer science research community in Mexico.

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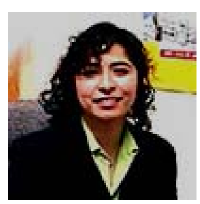
Jesús Favela *is a professor of computer science at CICESE, where he leads the Mobile and Ubiquitous Healthcare Laboratory and heads the Department of Computer Science. His research interests include ubiquitous computing, medical informatics and CSCW. He holds a BS from the Universidad Nacional Autónoma de Mexico (UNAM) and MSc and PhD from the Massachusetts Institute of Technology (MIT). He is a member of the ACM and former president of the Sociedad Mexicana de Ciencia de la Computacion (SMCC).*



Ana I. Martínez *is a professor of computer science at CICESE, where she studies the application of technology to organizational processes, especially in the health sector; she works on workflow, decision making, knowledge management, mobile computing and technology adoption. She received a PhD and an MSc in advanced computer science from the University of Manchester, UK, and a BSc. in computer science from UABC in Mexico.*

Marcela D. Rodríguez *is a professor in computer engineering at the Autonomous University of Baja California (UABC) where she leads a research group in Technologies for Ambient Intelligence. Her research interests include ubiquitous computing, autonomous agents and human-computer interaction. She holds a BS from the Autonomous University of Baja California, and a MSc and PhD in computer science from CICESE. She is a member of the ACM and Sociedad Mexicana de Ciencia de la Computacion.*

Víctor M. González *is a Lecturer in Human-Computer Interaction at the University of Manchester. He is an applied computer science researcher, focusing on studying and designing for the 'praxis' of work, personal and social spheres of human activity. He received a Ph.D. and Master degrees in Information and Computer Science from the University of California at Irvine and a Master degree in Telecommunications and Information Systems from the University of Essex, United Kingdom.*