The computational interplay of physical space and information space

Enric Plaza

IIIA, Artificial Intelligence Research Institute
CSIC, Spanish Council for Scientific Research
Campus UAB, 08193 Bellaterra, Catalonia (Spain).
enric@iiia.csic.es, http://www.iiia.csic.es

1 Introduction

There is nowadays a strong current in computer science to develop new devices and applications that transition from desktop (and laptop) computing to computing devices that are embedded in the physical and social environment in which people live. Several approaches have been proposed in this current and they have different names and focus on related but distinct issues. A first common trend, known under the names of *ubiquitous computing*, *pervasive computing* or *the disappearing computer*, focus on embedding the computing devices into the physical objects and surroundings where people work and live. A second, related trend is that of *wearable computers*, that focuses on embedding personal computing services in devices that people can carry or wear while moving around in their everyday activities. Next, *augmented reality* focuses on enriching people's perception of physical surroundings with computer-generated information. And finally, to be brief, there is a trend of developing autonomous agents that take on people's goals and try to achieve them on their own.

However different, a common issue they have to deal with is the awareness of the physical (and social) surroundings where people interact with the computing devices. Classically, computers (from the mainframes to personal computers) live in a purely informational world—typically, screens and printers, plus some customized connection to manufacturing machines or task-specific sensors. The advent of the Internet and the WWW links this computers into a common (or rather shared) information world. The relation of the Internet, as an information space, with the physical space is a research issue that essentially deals with the issues of context awareness: who is where and when, with whom, doing what. This paper focus on the interplay of physical space where people act and live and an information space where software programs reside, interact among them, perceive some properties of the physical world, and perform some tasks and actions on both the informational and physical spaces.

2 The interplay of physical and information spaces

Since all computers, and the software programs they run, are potentially connected over the internet, we can consider this as an "information space". Then, the computing devices that populate the physical world, from PDAs to the emerging "ubiquitous computing" devices, can be considered as the interface between the physical spaces people inhabit and the "information space" inhabited by software programs. The most critical issue to improve this interface is that nowadays software programs have little or no *awareness* of the physical space and of the activities people engage in that physical space.

In this paper we will first discuss the general issues that need to be addressed to improve the interfacing of physical spaces by the "information space" inhabitants, specially awareness of the physical and social context of people. Later, we will present the COMRIS project and we will explain how this general issues are addressed and solved for a specific physical space (a conference center) and a series of informational tasks useful in that space.

Awareness of physical space involves more than merely spatial or geographic reasoning. People perform activities and interact with other people while moving in physical space, and the more *aware* of those activities the better the interface with the information space. We can see here two levels required context awareness:

1. *Physical sensors*, determining the granularity of the perception of physical space activity. The physical sensors can be GPS (giving a coordinate point); wireless tags people wear and detect which person are close or in which room are they; or even more sophisticated speech capture and analysis systems (e.g. trying to determine topic, mood, etc, of ongoing activities).
2. *Common sense knowledge*, determining the inferences a system can made on the "world situation" given the physical sensor information. For instance, if a wireless tag informs that a person is in a room of type *Meeting Room* there is a series of inferences that can be done from a knowledge base that models business activities (e.g. the person is in a business meeting with other people and should not be interrupted —unless there is something urgent).

Perception using physical sensors establishes the baseline for awareness capabilities. For instance, GPS (Global Positioning System) can be used together with personal devices like PDAs to yield information customized to the person (using the person profile in the PDA) in that spatial situation (by a server that has a database of services available near that location). However, this approach is very centralized, depending on a service provider holding geographical information. For some tasks is better to add more sensors that allows to determine the person's *behavior*: a microphone can be used to determine if the person is busy (talking with somebody) or idle. Currently, project Esprit "IT for Mobility" 26900 is developing a sensor board that could be integrated with mobile phones or PDAs The sensors on this board include two microphones, a dual axis accelerometer, a digital temperature sensor and a touch sensor. With them, a computing device can locally infer different contexts where this device is situated: such as "sitting in a pocket", "lying on the desk", "in user's hand"—allowing the device to adapt its behavior to each context.

Even discussing the physical sensors used we have had to include the idea of a computational model that transforms the raw input data into some interpretation of the state of affairs in the world. This is because context-awareness is *essentially* an interpretation of the world situation, and as such what is needed is a lot of knowledge about what the world is like, in other words, common sense knowledge is needed. There has been a lot of research in Artificial Intelligence (AI) in the last ten to twelve concerning the issue *common sense*, with the *Cyc* project (`http://www.cyc.com`) being the most well known endeavor. We can summarize the current understanding of *common sense* in having two parts:

1. an ontology, defining the objects existing on the world that we want to talk about, and
2. an inference engine, capable of using a model the state of the affairs in the world expressed in that ontology to conclude new facts or statements about that state; new facts that are "obvious" or "implicitly" known by people, by what we are calling "common sense".

Moreover, context aware applications require to have some properties that differ from current applications: they need to be persistent, responsive, and autonomous. We will call this collection of properties *continuative computing*[1] because they set apart context aware applications from the usual application oriented to input-output. First, a context aware application needs to be *persistent*, i.e. persistently runtime state, non-terminating. Commonly, an application is oriented to input-output (in fact, the same definition of *algorithm* is based in the idea of transforming an input to an output) —an exception are programs that are operating system services (that are difficult to model in the algorithm paradigm based on *termination*). A common application is a file that when a user needs becomes runtime, receives an input and after some processing time yields a result and then goes offline.

A context-aware application needs to be non-terminating, awake and running persistently, much like an operating system or a PDA. Moreover, it needs to be persistent in order to be *responsive*: able to adapt and produce adequate responses when something changes in a context or the context changes to become a new context. Finally, context aware applications need to be *autonomous* in the sense of having an identity persistent in time and a memory (or internal state) that is individual. Since changing context is one of the most important information a context aware application can deal with it makes no sense that each particular physical space has a context aware application that is independent from other locations. Since persons move around is better to think of a context aware application as centered to users, like a PDA that a user carries around. In this way the context aware application can know the past history of contexts of the user, and even learn to anticipate the most likely future contexts of the user and prepare for it.

There is a current paradigm and associated technology that fits to these requirements we have outlined as *continuative computing*: intelligent agents. Agents and multiagent systems being developed in Artificial Intelligence are conceived of as autonomous, permanent entities capable of using ontologies to

[1] Continuative: tending or serving to continue.

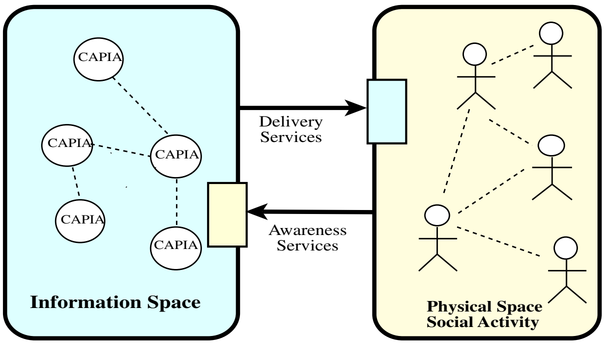

Fig. 1. A schema of the dual space of information agents and human users with the mediation services between them.

perform inferences for solving problems, and for cooperate and/or compete with other agents or people. Intelligent agents are classified as reactive or deliberative, depending on some design properties, but we will show later in the paper that designing agents with a particular architecture like the one we propose they can also be responsive and thus exploit awareness of physical an social context to improve their performance on behalf of users.

3 A Framework for Context-Aware Agents

Our framework is composed by a collection of context-aware personal information agents (CAPIAs) working in an information space and a collection of human users interacting in a same physical space. A useful way to visualize this distinction is the *dual space* schema depicted in Figure 1. Human users, on the right hand of Figure 1, are in a location, interacting with other persons (that might be users or not) in the context of social activities. Information agents, on the left hand of Figure 1, inhabit an information space where they interact with other agents and gather information in the interest of the users.

Moreover, we have *mediation services* connecting the information space of agents and the physical space of human users. Specifically, we are currently using two mediation services, namely an *awareness service* and a *delivery service* (see Figure 1).

3.1 Awareness and Delivery Services

The *awareness service* takes charge of pushing information from the physical space to the information space. Specifically, the awareness service provides to CAPIAs a real-time information about the physical location movements of users. The specific data provided depends on the particular sensors available in the awareness service for a particular application. For instance, in the conference center application the awareness service provides a real-time tracking of attendees location as well as the group of other attendees nearby a given attendee—see in Section 4 the features of the awareness service in the COMRIS Conference Center application.

Concerning the *delivery service*, it offers mediation and brokerage capabilities (subscribed by the human users) for delivering information from the information space to the physical space. Specifically, the delivery service provides the channels for delivering the information gathered by the CAPIAs to their corresponding users. For instance, in the conference center application the delivery service allows to send information as audio output by means of a wearable computer and HTML pages by means of screen terminals scattered through the conference building.

3.2 Agents Requirements

The society of agents has to be able to communicate using a common ontology for a specific application, and they have to share a collection of interaction protocols appropriate for that application. Our approach is to use the notion of *agent-mediated institution* [6] to specify the ontology and interaction protocols to be used by a society of agents for a particular application.

In addition to support the ontology and interaction protocols of an agent-mediated institution the agents should be able to manage with context awareness information. That is to say, a context-aware agent should be able to react dynamically when a new physical context information is received from the awareness service. Moreover, since the future physical and social context of the user is not known, a desired feature of CAPIAs is the capability of gathering information that may become relevant in a future context. For instance, in the conference center application, when an attendee is at a specific exhibition zone the CAPIAs use the knowledge provided by the conference about the physical distribution of booths for trying to anticipate the next movement of the attendee.

In our framework, context-aware personal information agents (CAPIA) are based on the distinction between two kinds of information valuation, namely *interestingness* and *relevance*. Information *interestingness* measures the intersection of a given information with the user model a CAPIA has for the tasks it is charged with. That is, $\textit{interestingness} : Info \times U_M \mapsto e_I$ where $Info$ is a given information; U_M is the user model; and e_I is the estimation of the interest that the user has in $Info$. For instance, in the conference application a preliminary criterion for determining the interestingness of a given paper presentation is performed comparing the user interests (described as a collection of topics with different weights) and the keywords associated to the presentation (also described as a collection of topics with different weights). Then, other criteria such as the knowledge about the speaker or the users agenda increase or decrease the initial assessment.

However, depending on the physical and social context of the user and on the time some information may be more or less *relevant* for the user on each particular point of time. Information *relevance* measures this intersection of a given information with the time and the context of the user. That is, $relevance : Info \times time \times UC \mapsto e_R$ where $Info$ is a given information; U_C is the user context; and e_R is the estimation of the relevance of $Info$ in U_C. For instance, in the conference application when an attendee is nearby to an exhibition booth, the information related to the booth is estimated as more relevant. Another example of increase of relevance is when a conference event is close to start: a CAPIA has a time constraint for deciding if that event is useful for the user interests.

We can say that, basically, the CAPIA go on their tasks, interacting with other agents (and other accessible information resources), to gather information that is *interesting* for their users. Concurrently, each CAPIA uses an *awareness service* (see below) to keep track of the whereabouts of its user and decides which information is *relevant* for her in a particular physical and social context. Clearly, *interestingness* and *relevance* are not completely independent, and the information gathering is correlated with the information the agent expects to deliver to the user, but for exposition purposes it comes handy to talk about them separately.

At this point it is useful to specialize this framework in a concrete application to illustrate the dual space and the personal information agents exploitation of context awareness.

4 The Comris Conference Center

This section introduces the framework of context-aware information agents in a particular application, that is to say in the physical location and the social activity context of a Conference Center in the COMRIS[2] project. We view the Conference Center (CC) as an agent-mediated institution where a society of information agents work for, and are aware of, the attendees of a conference [7]. The ontology of the CC institution defines the conference activities that take place in the CC. Examples of conference activities are exhibition booths and demo events, plenary and panel sessions, etc. The ontology also defines the roles that a person takes in different locations while performing different activities, e.g. speaker, session chair, attendee, organization staff, etc. Other important elements defined by the CC ontology are the different locations of the conference such as the exhibition areas, the conference rooms, and the public areas—i.e. halls, cafeterias, and restaurants. This information is used by the agents for reasoning about the movements of users in the conference. The schedule of conference events is also defined in the CC ontology.

Finally, the CC ontology supports the definition by each user of the “instruction set” that her CAPIA should follow. The instruction set is entered by the conference attendee using a WWW browser while registering and basically includes i) an interest profile (specifying the topics with weights the attendee is

[2] COMRIS stands for Co-Habited Mixed-Reality Information Spaces. More information is available at URL `<http://arti.vub.ac.be/~comris/>`.

interested in), ii) those tasks the user commissions the PIA to do in her behalf (e.g. if she is interested or not in making appointments); and iii) the delivery modes that the CAPIA will use to communicate with her.

We implemented two types of CAPIAs in the conference center application: CAPIAs representing interests of attendees and CAPIA advertisers. There is a CAPIA for each attendee, a CAPIA advertiser for each exhibition booth, and a CAPIA advertiser for each paper session. The goal of CAPIA advertisers is convince people for attending to the conference event they are representing.

4.1 Delivery Service

The delivery service in COMRIS allows the users to receive information in two ways: by means of a wearable computer with text and audio output and by screen terminals scattered through the Conference Center. The wearable computer is used to convey short messages that are relevant for the user with respect to her current physical and social surroundings. The user can walk to a terminal if she wishes to have more information about this message or other recent messages she has received. When the user approaches a screen the wearable computer detects this terminal's identifier, and then it sends this identifier to the user's CAPIA. Once the CAPIA is aware of this situation, the agent sends to that screen the report of the performed tasks and the report of ongoing tasks.

The delivery service comprises several components. The first component is the natural language generation (NLG) component. The NLG component receives the message sent by a CAPIA and generates an english sentence explaining the message content and taking into account the current attendee context and the sentences previously generated. Then, when the message has to be delivered as audio, the sentence structure is sent to a speech synthesis component that produces the actual audio heard by the user. Similarly, there are components that transform CAPIA's messages into HTML or VRML in order to be delivered to the screen terminals.

4.2 Awareness Service

The awareness service keeps track of the whereabouts of the attendees in the Conference Center. In the COMRIS CC the detection devices are a network of infrared beacons (marking the different rooms, places and locations in the CC) and the wearable computers the attendees carry. The COMRIS wearable computer (shown in Figure 2 and commonly called *parrot*) detects the infrared beacons and thus informs the awareness service of the location of its user. Moreover, the wearable device possesses an infrared beacon, allowing the detection of other persons, wearing a parrot, located nearby. In order to have access to this information, each CAPIA in the information space "subscribes" its user to the awareness service. As a result, the CAPIA receives messages about the changes in location of that person and a list of other people close to that person. When the CAPIA interacts with other CAPIAs (representing other conference attendees), and decides that those CAPIAs are interesting persons, subscribes those

Fig. 2. The wearable computer also known as "the parrot". The CPU is on the front unit while the back one hosts sensors and batteries.

persons to the awareness service. Consequently, the CAPIA is aware of the location of the most interesting persons for its user, and detects for instance when one of these persons is in the same location as the user—a most relevant situation to push to its user the information concerning that person that is interesting *and* nearby.

Tasks The tasks that the Comris Conference Center supports are the core of the activity in the CAPIAs. It is important to remark here that, in order to perform these tasks, the information agents use *both* the CC ontology and the awareness service to infer the situation of the user. That is to say, knowing that the user is in a particular place, the current time, and the activity scheduled by the Conference for that place at that time, the information agent can infer the social activity in which the user is involved.

We will briefly summarize the tasks performed by Comris CAPIAs and the scenes they are involved in.

• *Information Gathering*: is responsible of establishing initial conversations with other CAPIAs for estimating the interestingness of the attendees or conference events they represent. We say that the information gathering task constructs the *interest landscape* of a given attendee. The interest landscape holds all the information considered as useful for the interest of the attendee and is used and refined in the other tasks. When the information gathering task assesses a conference event with a high interestingness valuation, the information is directly

delivered to the attendant. This delivery strategy was adopted for biasing the future decisions of the attendee. In CAPIA advertisers, this task has been specialized for attracting persons that might be interested in the conference events (exhibition booths or conference sessions) they represent.
• *Appointment Proposal*: in this task, using the interest landscape, the CAPIAs try to arrange an appointment between two attendees. First, CAPIAs negotiate a set of common topics for discussion (the meeting content). When they reach an agreement, CAPIAs negotiate on the appropriate meeting schedule.
• *Proximity Alert*: in this task an attendee is informed that she is physically near to another person with similar interests —or near an exhibition booth or a thematic session with similar topics.
• *Commitment Reminder*: this task is responsible of checking if attendees are aware of their commitments. The CAPIA uses context to determine that the user may be unaware of a commitment, e.g. if she is not near the location of an appointment (or a bus scheduled to leave) a few minutes before. Commitments of attendees are only noticed when the context information available to CAPIAs indicates that the attendee is not aware of the commitment (e.g. it is five minutes before the starting of a session chaired by the attendee and the attendee is physically in another place).

For each task several *activities* are launched in the CAPIA. For instance, when an agent in Comris is discussing about appointments with several CAPIAs, each thread of interaction is managed by a distinct activity. The activities can start either by an internal decision of a CAPIA or because a CAPIA has received a request from another CAPIA.

5 Conclusions

We have shown a specific context-aware application (the Comris Conference Center) developed in the framework of the Comris project that illustrates. We have seen that the physical infrastructure, consisting of an individual wearable computer and localization beacons, was used as a "awareness service" by a society of agents inhabiting the information space. We have focused on the kind of software required to develop a context-aware application, showing that using an agent-based approach we can fulfill the properties we required in what we called *continuative computing*. We also discussed the kind of agent architecture that can exploit context-awareness.

The approach we presented was based on the idea of having a personal agent per person. This allows the continuative dimension of processing to be user-centered. As the user changed context, her personal agent received the corresponding perception data from the awareness service and followed the user to a new physical context. In addition to this, services that need to be provided *to* the users (services provided by the Conference organisation in our example) are agentified, i.e. they are also provided by agents (and they also are aware of the contexts they are interested in). Moreover, this approach is scalable: the agent could use another different awareness service on a different conference center.

Moving from one application context to another (from one conference to another) requires a standardization effort of the awareness services, but this effort is reasonable since it can improve the performance and lower the costs.

We see thus that context-awareness can be integrated into an agent-based paradigm in a well understood way. A better infrastructure on context perception, as we can expect to be developed in the next decade, can be integrated in the agent-based paradigm without major problems. The main reason for this is the AI approach to agents that employs ontologies describing the world. Clearly, with a better perception infrastructure the agents could perform better inferences about the state of the world. For instance, in the COMRIS conference center the agents knew when two persons were in the same room (using beacons) and when two persons were one in front of the other (using the wearable computer beacons), but since there was no microphone on the wearable computer there was no way to know if the user was already busy talking with someone or not.

In addition to improved awareness services and perception infrastructures, a second issue that was considered in the COMRIS project but never tried was that of learning. Agent learning is developing into an active area of research, initially focused on reinforcement learning but it is rapidly broadening. Agents in context-aware applications should be able to adept to new contexts but also to learn from the user satisfaction (or not) of the agent's action. However, learning from examples requires a sufficient number of examples to be worthwhile, and the experiments conducted in the framework of the COMRIS project assumed that the Conference only lasted one day—and the amount of data was too sparse to allow significant learning. It turned out that learning would be interesting if personal agents were carried over by the user to different conferences, allowing the collection of examples significant enough in number and variability. Only when awareness infrastructures are more proficient and more readily available (and awareness services are more standardized, allowing agents to continue from one application context to the next) the AI and agent technologies will be able to respond ubiquitously and intelligently to the requests and the needs of people.

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