

An Interaction Model and Infrastructure for Localized Activities in Pervasive Computing Environments

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Abstract—This paper presents an interaction model for pervasive computing environments supporting localized activities, i.e., activities strongly associated to a specific physical environment. We are particularly interested in activities performed by occasional visitors to public spaces. This interaction model is characterized by an activity-centered approach to pervasive computing and is defined in a conceptual model inspired by Activity Theory. ActivitySpot, a software infrastructure implementing this conceptual model, is also presented. User interaction in ActivitySpot is based on simple, everyday pervasive computing devices, which facilitates usage learning and allows for a wide user population. ActivitySpot has supported the deployment of several pervasive computing solutions for localized activities. Our conceptual model has been evaluated by user studies run at different public spaces and global results demonstrate the model's suitability to the targeted type of scenario.

I. INTRODUCTION

Public spaces are a common scenario for pervasive computing. In these environments, we find many kinds of users and activities. Entertainment, education, health, shopping, or public administration are some examples of areas in which public spaces are the focal point of human activity. The activities that can be performed in public spaces vary between those which can be carried out everywhere – their relevance or interest is not associated to the physical environment (e.g., managing e-mail or editing a report) – and activities that can only be physically achieved or acquire special relevance in a specific place (e.g., visiting an exhibition at a museum or visiting a relative at the hospital). This work is focused on the latter, which we call *localized activities*, because they are strongly related to a specific physical location.

Some people are recurrent users of the places where localized activities occur (e.g., local workers) while others go there occasionally for very short-term work, for achieving some formality (e.g., public administration), for meeting with somebody, or just for entertainment. Particularly challenging, from the point of view of actors – those who are involved in the activity –, are localized activities performed by *occasional visitors*, i.e., by people that are not used to live or work in a

place and that occasionally pass by. When arriving for the first time to a particular public space, they have little or no idea about the physical setting nor about the resource infrastructure that such an environment may provide to assist localized activities. These users need help to easily orient themselves in the physical environment, to identify the resources (humans or artefacts) available for achieving the activity, and to perceive how to interact with the available resources.

Public spaces, in general, are designed and instrumented to provide some assistance to their visitors. They may have wall signs, panes, public digital kiosks, staff members, brochures, receptacles for comments and suggestions, etc. However, that type of support is normally targeted to the functional aspects of the space and very limited in providing people with a personalized and rich view of how the space can assist them with their needs and enhance the execution of the activities they intend to perform at that place. Pervasive computing represents a major opportunity for enhancing the experience of occasional visitors to public spaces, by offering them effective means for achieving their localized activities, while providing a personalized support. Moreover, pervasive computing interaction artefacts (e.g., public screens, RFID tags, mobile phones, etc.) are becoming increasingly cheap, thus allowing for widespread availability throughout public spaces. However, for pervasive computing solutions to be truly successful in the scenario we are considering, they must follow a design approach that is effectively capable of transparently supporting activities that take place in the physical world.

This work is based on the assertion, shared by many authors, that such goal can only be achieved by adopting an activity-centered approach to system design [1], [2], [3], [4], [5]. The usual desktop application- and document-centered models are unsuitable for pervasive computing scenarios, because they oblige humans to dedicate considerable efforts in manipulating the tool, rather than focusing on higher-level concerns. Visitors to public spaces will not sit in a comfortable chair in front of a desk, but will rather be moving within buildings or streets, possibly in a hurry, with one or both hands taken. Furthermore,

pervasive computing systems are going to be used by all kinds of people, and not only by a computer-educated population. Such a computing system cannot require too much attention, if possible any attention at all, so that humans can use the computer unconsciously [6]. Ideally, people should perform an activity requiring computing tools as they perform any other activity, by focusing on the activity itself, and using the computing tool as naturally as any other tool.

An activity-centered approach becomes even more important in situations in which people have little or no prior knowledge about the local means available for the activity they are going to perform. The only thing visitors are often aware of is the generic goal or motive for their activity. Therefore, providing them with an activity-centered support is of utmost importance: it considerably eases the process of adapting to the system support and does not add to the difficulties helpless visitors may face.

The overall objective of our work is to develop an activity-centered framework for providing occasional assistance to people during the execution of localized activities. This framework is composed of a conceptual model that represents both the activities a public space is able to support and the relationships between interaction devices and activities. We have developed a software infrastructure that implements that conceptual model and enables the deployment of activity-centered pervasive computing assistance to localized activities, making use of varied user interaction means. We sustain the validity of our approach by evaluating the opinion of end-users regarding: compatibility of the proposed conceptual model with their own mental model of activity; easiness of interaction; and utility. This evaluation was conducted during three user studies held along one year with different public spaces and activities.

In the following section, we describe the main challenges our work deals with. We next present our Activity Theory-informed conceptual model for representing activities and user interaction. Section IV presents ActivitySpot, the activity-centered software infrastructure we propose for supporting localized activities. Section V reports the user studies we carried out with our framework and discusses its results. Finally, section VI presents some of the related research and section VII concludes the paper.

II. CHALLENGES

The development of an activity-centered framework for providing pervasive computing assistance for occasional visitors raises many research and deployment challenges, from lower to higher level issues. In this work, we have focused specifically on two of those challenges: modelling localized activities and modelling user interaction with pervasive computing devices.

A. Activity model

We understand activity model as the way a particular activity structure is represented in a human- and machine-understandable vocabulary, so that it can be both effectively

communicated to users and implemented in a pervasive computing infrastructure. Representing how humans perform an activity is a difficult task, as people may have different mental models of the same activity. Furthermore, the informal and rather unpredictable nature of the activities addressed in this work severely affects the efficacy of more structured approaches to formalizing the steps that compose an activity, such as those used in work-flow systems [7]. There is therefore a trade-off between the need for a generic model of activity that can be instantiated by an activity-centered infrastructure for different application scenarios and the risk of imposing our view of activity on heterogeneous mind-sets.

A generic activity model must thus focus on what is less dependent of individual mind-sets for carrying out an activity. The potentially multiple activities that a public space may support must therefore be represented in a machine-understandable model describing which functionalities and interaction media are available to each activity, while enabling modularity and reuse of system components by different activities. This model must also be simple enough to require no learning effort from the end-users themselves and minimum specific know-how and effort from public space administrators managing pervasive computing assistance to localized activities.

An activity model may also depend on contextual and personal factors (e.g., elderly or disabled people have to perform an activity possibly in a very different manner). Thus, an additional challenge is how to add context-awareness to an activity model. User context is also fundamental when deciding which localized activities is the user interested in accomplishing (e.g., a person that arrives at the hospital reception may go there for different reasons: for visiting a relative, for a consultation, for equipment maintenance, etc.).

B. User interaction model

Occasional visitors to public spaces do not have the time to learn how to use a previously unknown pervasive computing system. Therefore, user interactions must be very simple and usage instructions must be blended with the environment and the system itself. We assume that visitors will not focus on a single interface to accomplish some task, but rather that interaction is more free flowing, like our interaction with the rich physical world of people, places, and objects in our everyday lives [1]. In our vision, a pervasive computing environment is thus potentially instrumented with heterogeneous interaction devices, each with its own functionality, and is used by visitors who also bring their own personal devices. The challenge is how to deal with this heterogeneity while not compromising the simplicity of user interaction.

Another challenge is to deal with the possibly varied interaction devices the same person may use within the course of an activity and to make that person feel that all those interactions, whatever the device used, are integrated and all part of the same activity. This is particularly challenging because each interaction must be identified in order to be integrated with others from the same visitor. Since users may not have

previously visited the space, we cannot assume the existence of a local personal profile or information about a particular user and her/his interaction media. Unless some form of automatic, universal visitor profile capture is available, which is not expected in the near future, visitors have to provide themselves their own information to the local infrastructure, e.g., through some initialization procedure.

III. MODELLING ACTIVITY AND USER INTERACTION

We believe that the best approach to overcome the activity and user interaction modelling challenges is to ground our research on previous work on human activity analysis. The importance of a theoretical framework of human activity is that it provides pervasive computing researchers with an agreed set of terms to describe activity and with concepts that drive them in the construction of systems that intend to support activity [8]. Among several frameworks produced mainly by the fields of psychology and philosophy, we chose Activity Theory (AT) [9] as the background for this work, based on its maturity acquired along several decades of research and its set of simple and solid concepts. AT has been recently further developed, mainly by Engeström [10], and applied to several areas in computer science [3], [8], [11], [12], [13], [14]. Among the concepts of AT, we are particularly interested in the different levels of analysis of an activity: activities, at the uppermost level, are distinguished on the basis of their motive and the object toward which they are oriented; actions are distinguished on the basis of their goals; and, finally, operations, on the basis of the conditions under which they are carried out. For example, an activity motivated by food is composed of several goal-oriented actions (e.g., collecting ingredients, preparing a recipe, etc.) and operations which vary in function of conditions (e.g., going to the kitchen-garden, picking vegetables, taking ingredients from the fridge, etc.).

An activity may be carried out in a variety of ways by employing different actions and operations, which may respectively be part of different activities and actions. Individual characteristics and changing local and personal context are the factors driving the structure of a localized activity. For example, a public space like a museum may support different activities, which in turn may employ different actions and operations, all depending on several factors, like the visitor role (e.g., regular museum visitors, authors, external security inspectors, etc.), age, preferences, or available resources. A particular characteristic of human activity is that it is mediated by tools – psychological (e.g., mental plans) or physical (e.g., a computer). Each operation may require some tool to be executed. When a tool executes an operation automatically, it allows the individual to concentrate on actions and activities, freeing her/him from low-level efforts. Pervasive computing artefacts can be seen as tools that may be used for the execution of operations, allowing the visitor to concentrate on the higher level aspects of her/his activity. Figure 1 depicts our AT-inspired abstract model of activity applied to the museum example.

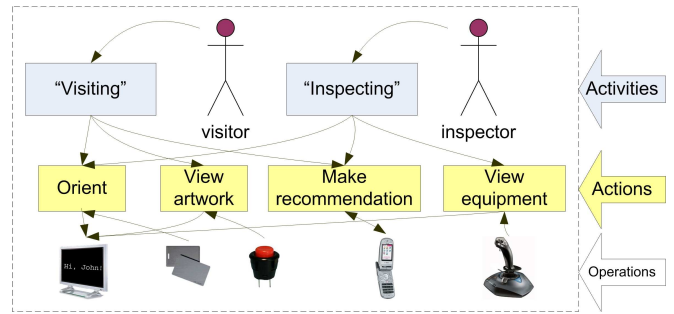


Fig. 1. An activity-based model for a pervasive computing environment

For the sake of clarity, the model omits the details of operations. In a pervasive computing system, an operation can be a user interaction, a sensor read, a web-service request, a database query, etc. We just represent the user-facing devices, which are the most visible part of operations. The model exemplifies how flexible an activity structure can be: a plasma screen can be used both by visitors and inspectors to achieve different actions; an “orientation” or a “make recommendation” action can be executed in different activities, with different goals in mind (a recommendation made by a visitor has a different goal from a recommendation made by an inspector).

Given that user interaction with a pervasive computing system is performed through multiple, heterogeneous means, and that an activity may be carried out by making use of many different interaction means, it is necessary to decouple interaction from activity, so that changes in the interaction means do not considerably affect how the assistance for an activity is implemented. This is achieved by reducing user interaction analysis to basic human-computer interaction concepts: stimulus and response. We assume that, for a given stimulus through a given device, a response is produced through the same device or other device or set of devices.

We also assume that people interact with pervasive computing systems mainly through simple devices. We consider a simple interaction device in a pervasive computing environment as being the equivalent to a mouse, a keyboard, or a screen in a desktop computer. Stimuli and responses descriptions are made available to activity-centered pervasive application developers as mouse, keyboard, and screen events are made available in APIs to graphical user interface frameworks. We are talking about elementary, easy-to-use interaction means that cannot be used only by themselves to carry out an activity. The execution of an activity is thus distributed by the interactions made with each of those devices. Every user interaction, whatever the underlying medium, must be framed within the user activity and integrated with other previous and further interactions, becoming more meaningful and contributing to compose the whole activity. Another characteristic of our user interaction approach is that it does not bind users to a limited set of devices. By taking device heterogeneity into account in its foundations, our framework enables usage by a wide, potentially unlimited user population.

IV. THE ACTIVITYSPOT FRAMEWORK

The ActivitySpot framework provides a set of conceptual and software tools for designers and developers applying an activity-based approach for assisting occasional visitors to pervasive computing environments. The concepts basing the framework are derived from Activity Theory, namely those associated to the activity structure analysis, i.e., the concepts of activity, action, and operation, as well as the activity structure flexibility. We also consider that activities and actions depend on local and personal context, either as an execution condition or as a variable influencing the response of an operation. Finally, the framework includes the basic concepts of stimulus and response to model user interaction. The conceptual model is implemented in the architecture described in section IV-B. The model omits operations because, as stated in the previous section, these correspond to details of actions that are not executed consciously by visitors. Even the most visible part of operations – stimuli and responses – is desirably a transparent part of user interaction.

ActivitySpot includes a runtime infrastructure (see section IV-B) for coordinating interaction with local devices and associating those interactions with the execution of actions within localized activities. The behavior of the system is determined by a specification of the local environment (see section IV-A) in terms of the existing localized activities, the actions composing them, and the interaction devices available in the physical space for carrying out activities. We assume that an ActivitySpot-enabled public place provides its visitors with instructions about the pervasive computing assistance to their activities, a sort of human-understandable version of the environment specification. Given that interaction is based on elementary, everyday devices, visitors should not find trouble in quickly learning how to carry out their activity with ActivitySpot. However, the success of learning also depends on the way instructions are presented to visitors.

A. Environment specification

In order to be independent of physical space and activities and thus support any localized activity scenario, the ActivitySpot framework is based on a generic specification format for activities, actions, and interaction devices available in an environment. Each environment supported by ActivitySpot has a specification of: a) which actions can be executed – name, supported stimulus and response types, a reference to the component implementing the action controller, and execution conditions (e.g., “action A is available only to users playing the ‘inspector’ role”); b) which activities are available – name, references to the actions composing it, and execution conditions (e.g., “activity B is available at week-end only”); and c) which devices can be used – stimulus or response type, physical location, and references to other devices which have some physical or logical association.

Before advancing to the environment specification phase, pervasive computing designers should perform some sort of task analysis [15] or, more properly, use a tool such as the Activity Checklist [16] or the Activity Model [8], in order to gain

an understanding of the needs and context in which visitors perform their activities. The result of this preliminary phase is the identification of the activities and respective actions that the pervasive computing environment is going to support. Then, developers implement the behavior of each identified action by developing the respective action controllers, i.e., by programming every possible response to the stimuli to which that action reacts. This part of the development corresponds to the implementation of operations in the activity structure. Currently, the ActivitySpot infrastructure is supporting Java-developed controllers, all of them implementing a common interface, allowing a loose coupling between the infrastructure and controllers implementation. Action controller developers do not have to worry with the details of stimulus reception or response generation, because appropriate abstractions are provided by the ActivitySpot API.

As the same action can be part of different activities, the same action controller can be also reused in different activity specifications. Likewise, reuse can be achieved at the operational level, by reusing the implementation of common operational behavior between different actions. Reuse is potentiated not only within the software developed for a specific public place but as well at a broader marketplace perspective, for instance, by creating an action controller market, where one could find the support for actions common to many different scenarios.

Environment specification is currently done by means of an XML document which is then processed by the ActivitySpot runtime infrastructure. This XML document can be generated by a graphical user interface providing high-level abstractions easing the environment specification process.

B. The ActivitySpot architecture

The ActivitySpot architecture (figure 2) implements the activity-centered conceptual model described earlier. Following the generic character of the environment specification, the ActivitySpot architecture provides abstractions powerful enough to be instantiated in several concrete scenarios.

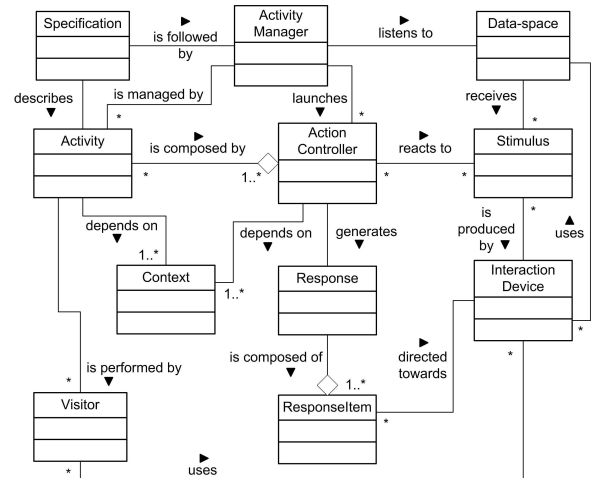


Fig. 2. The ActivitySpot architecture

The main architecture component is the Activity Manager. It manages activity execution by coordinating stimuli processing, context heuristics verification, and response generation. The Activity Manager, following the environment specification, knows the characteristics of each supported activity, the respective actions, and the interaction devices available in the environment. At start-up, the Activity Manager loads all the specified action controllers into memory and listens to the specified interaction devices, waiting for visitor stimuli.

We assume that visitors, previous to the system usage or during the activity unrolling, provide the infrastructure with information about their personal profile and interaction devices (e.g., by performing a registration step). We currently do it by employing ad-hoc mechanisms, such as providing the mobile phone number through an initialization message or associating RFID tags or a Bluetooth address to a visitor at a registration desk. Visitor data are kept in a relational database which is also used to keep the activity state for each visitor.

Another crucial component is the EQUIP data-space [17], which is used as a communication middleware between interaction devices and the Activity Manager. The Activity Manager listens to the stimuli made by visitors by subscribing to corresponding event types in the data-space. Whenever a visitor generates a stimulus through an interaction device, a corresponding stimulus description is sent as an event to the data-space. The Activity Manager senses this stimulus and identifies its author (e.g., through a mobile phone number, a MAC address, an RFID code, etc.). Then, the Activity Manager triggers all the action controllers that support the respective stimulus type. Each of these action controllers processes the stimulus sent by the Activity Manager and, in the case the stimulus was effectively targeted to the respective action, an adequate response is produced – a response may be composed of one or several response items directed towards specific interaction devices. The Activity Manager sends the response items to the data-space, which propagates them to the interaction device presenting that response type. When several devices may consume the same response type, the Activity Manager is able to address the response item to the device that is physically closer to the user. This is achieved when the Activity Manager is able to derive the user location from the stimulus. For example, if an RFID tag carried by the user is intentionally brought near a reader, the user is expecting to see the response in a nearby display, not in a display elsewhere.

The stimulus reaction behavior is similar to what happens for an event generated by a context sensor. Actions that are sensible to context changes may thus generate a response to an interaction device or, if a response is not suitable, execute some logic without producing any response. Every executed operation (either as a consequence of a stimulus or a context change) is recorded in the Activity Manager database and may be later retrieved to check the activity state or to influence the outcome of other operations.

The only requirements of the ActivitySpot infrastructure are a Java Virtual Machine and EQUIP-compliant adapters for each interaction device available in the environment. The

interaction device and context sensor types supported by the infrastructure are unbounded, because the infrastructure can be extended (without needing recompilation) to support new types. The following diagram depicts the instantiation of the ActivitySpot architecture in a concrete scenario.

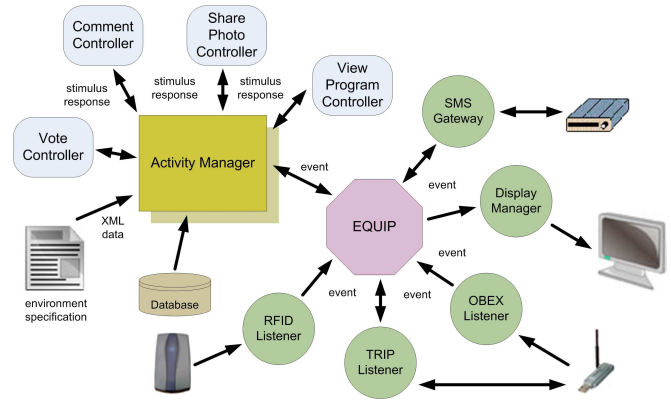


Fig. 3. An ActivitySpot instantiation (arrows indicate data flow)

V. USER STUDIES

The evaluation of the ActivitySpot framework takes into account whether the conceptual model and the user interaction we propose is adequate to the cognitive challenges faced by occasional visitors to public spaces. The evaluation goals we defined, based on the challenges described in section II and inspired on several reference evaluation models [16], [18], [19], [20], are namely:

- compatibility of the conceptual model – visitors understand the assistance that is being offered to their activity; visitors find that the conceptual model of the provided assistance is compatible with their own mental model of the same activity; visitors understand that all interactions are integrated into their activity.
- user interaction – visitors are able to successfully execute actions without any previous training or help other than the concise visual instructions provided to them; visitors consider that the system responds to their stimuli in a timely and predictable manner; visitors consider the effort required by the system does not divert them from their activity; visitors consider that the initialization procedure is not disruptive.
- usefulness – visitors consider that the system helps them achieving the goals for their activity, preferably more effectively when compared to alternative situations (conventional assistance, single application in mobile phone, and interactive kiosk); visitors consider that the personalization provided by the system is adequate to their needs.

We have evaluated ActivitySpot in three different user studies, collecting data from surveys, observation, and log analysis. We further describe each of the user studies and we conclude the section by discussing the evaluation results.

A. PhD poster session

The first user study was conducted during a one-day PhD poster session in our university campus. We deployed support for two different activities: visiting the poster session and presenting a poster. Although in both cases many users were university members or students, the scenario, as an extraordinary event, provoked the situation that characterizes our work: novelty of activity, physical setting, and infrastructure support. Both activities took place in the poster exhibition area. ActivitySpot was evaluated by 15 users (4 women and 11 men), with ages ranging between 24 and 44.

Users had to explicitly choose their activity by sending an initialization SMS message to the ActivitySpot SMS center. Afterwards, they went to the registration desk in order to obtain a pair of RFID tags that later allowed them to execute particular actions. Users were also given an evaluation survey to be returned at the end of the poster session. Within the exhibition area, two interaction spots were available, each with public displays, RFID sensors, and Bluetooth and infra-red connectivity. The actions installed for the supported activities were:

- At a public display, after reading an RFID card in a nearby sensor, users could see an overview of the exhibition containing the exhibition plan and the title of the most interesting posters.
- After reading an RFID keyring near a public display, users could view their activity state. Poster visitors could view the title of posters they bookmarked, information about related posters, and submitted comments. PhD students could view comments and the number of votes and bookmarks made to their own poster.
- Comments to a poster could be posted through SMS (e.g., sending a “cmt p5 interesting work” message, in which ‘p5’ refers to the poster id). A confirmation response was generated over SMS. Only poster authors could later read the comment through a Web interface.
- Voting for a poster (available only for users engaged in the poster presentation activity) could be done through SMS (e.g., sending a “vot p5” message). A confirmation response was generated over SMS.
- Posters could be bookmarked by sending an SMS (e.g., “bmk p5”). A confirmation response was generated over SMS. Bookmarked posters could later be accessed via a Web interface.
- Photographs taken at the exhibition could be shared and viewed at the public displays by sending the picture over Bluetooth or infra-red to the system.
- Users could make any public comment to be presented at the public displays. This was achieved by sending an SMS (e.g., “msg Great exhibition!”). Seconds later, the comment appeared at the public displays.

B. Cultural center

In this scenario, a six week long study held at a cultural center, we aimed at assisting spectators at three different moments of the shows: before, at the interval, and afterwards. The

activity was composed of actions allowing spectators to obtain detailed information about the current show, post comments and photographs, view information about next shows, vote for the current show, or view information about the activity state. Interaction spots, composed of public displays, RFID readers, and Bluetooth connectivity, were installed at the entrance hall of two theaters. Additionally, a dozen of 2D codes associated to different actions were stuck to the hall walls and pillars.

Most visitors spontaneously addressed themselves to the ActivitySpot registration desk after reading leaflets or looking at public displays’ advertisements. At registration, visitors were asked to provide their name, mobile phone number, and were given a pair of RFID tags and a leaflet describing what actions were available. Short instructions about system usage were spread near the public displays. Visitors owning a Bluetooth- and camera-equipped mobile phone also received (through Bluetooth push) a 2D code reader application¹ and installed it in their mobile phone. This process allowed us to associate a visitor to the respective Bluetooth MAC address. Since there were no simultaneous shows, ActivitySpot implicitly inferred the intended activity, i.e., the activity was automatically initialized for the current show after the first interaction made by the visitor.



Fig. 4. ActivitySpot being used at the Cultural Center

Visitors had different interaction alternatives for executing the actions composing their activity:

- Voting for the current show could be achieved through SMS (e.g., sending a “vote 5” message) or 2D codes (capturing the 2D code corresponding to the intended vote). A confirmation response was generated for SMS stimuli.
- Comments could be posted through SMS (e.g., sending a “comment what a wonderful play!” message) (figure 4, left).
- After reading the RFID card near a public display, visitors could view in the same display detailed information about the current show.
- Activity state (what was done and what could still be done) was viewed in a public display after reading an RFID keyring in a reader nearby.
- Photographs taken at the cultural center could be shared and viewed at the public displays by sending the picture over Bluetooth to the system.

¹The 2D code reader application was based on the TRIP project [21].

- Information about next shows could be viewed in public displays after capturing a corresponding 2D code placed near the display (figure 4, right).

During the period ActivitySpot was running in the Cultural Centre, a total of 24 participants (18 men and 6 women), with ages ranging between 21 and 39, volunteered for participating in the evaluation. In order to engage participants in the evaluation, their effort was compensated with tickets for shows. Participants could choose between using ActivitySpot only once or as many times as they attended shows in the Cultural Centre. In the latter case, registration to ActivitySpot was made only once. At registration, participants were given a survey that they returned after the last show they attended to.

C. Conference

The last user study was held during a three day conference on human-computer interaction. Three different activities were supported, depending on the goals of conference participants: authors presenting their work, conference organizers, and conference participants who were not presenting any work (as main authors). We introduced in this user study some improvements that derived from lessons learned in the two previous studies. Prior to the study itself, we made an activity analysis, by submitting surveys to people who usually participate in conferences, in order to obtain their view of the activity, i.e., which goals they establish and which actions they execute in order to accomplish those goals. This information helped us identifying the actions that could better meet user needs. After this phase, a prototype description (interaction details for each available action) was evaluated by a human-computer interaction expert, who identified some minor interaction problems.

Conference participant data was obtained beforehand in order to build a basic profile (name, institution, and work authorship) that was used as a source for the contents of some actions and for speeding up visitor registration. During the conference, participants were asked to enroll in the study, by registering at the ActivitySpot desk. This registration step lasted about a minute – just the time for asking the participant name, desired activity, mobile phone number, research interests, and delivering two RFID tags. If a participant was using a Bluetooth- and camera-enabled mobile phone, an additional step – obtaining automatically its Bluetooth MAC address – was required.

Two interaction spots (public displays, RFID sensing, and Bluetooth connectivity) were installed at the reception hall, where coffee breaks also took place. 2D codes were also stuck to the walls. A total of 8 participants (7 men and 1 woman), aging between 25 and 42, used the system and answered the surveys. A second group of participants (6 people) was selected as the control group, in order to assess how the pervasive computing assistance contributed to achieve activity goals, compared to the conventional assistance available in conferences.

The actions installed for the supported activities were:

- Viewing the conference program, at a public display, after reading an RFID card in a nearby sensor; only the next three events were presented, with events matching personal research interests highlighted. Other actions were recommended, based on the activity state.
- Viewing the participant list, at a public display, after reading an RFID keyring in a nearby sensor; three participants were randomly presented, those matching personal research interests with more chances to be presented. Other actions were recommended, based on the activity state.
- Comments to a work could be posted through SMS (e.g., sending a “comment p5 interesting work” message, in which ‘p5’ refers to the paper or poster id). A confirmation response was generated over SMS. This comment was immediately delivered to the paper or poster main author through SMS or e-mail.
- Rating a work (not available to conference organizers) could be done through SMS (e.g., sending a “vote p5 4” message). A confirmation response was generated over SMS.
- Each conference day could be rated by sending an SMS (e.g., “rate 5”) or by picking a 2D code (five codes, one for each rating, were stuck at the auditorium entrance) with the 2D code reader. The rating was attributed to the conference day on which the message was sent or the 2D reading was done. A confirmation response was generated over SMS or on the 2D code reader application. This action was not available to conference organizers.
- Photographs taken at the conference could be shared and viewed at the public displays by sending the picture over Bluetooth to the system.
- Viewing work ratings (available only to authors) or conference ratings (available only to conference organizers), by sending a “view” SMS message. The response was an SMS message containing the rating average.
- Conference organizers could broadcast any public advertisement to conference participants. This was achieved by sending an SMS (e.g., “advertise Conference restarts at 2p.m.”). The advertisement was then sent through SMS to all conference participants registered at ActivitySpot and was also shown at the public displays.
- Undoing the last action through SMS, by sending an “undo” message. The last undoable action (photo sharing, work or conference ratings) was then cancelled.

D. Results

In all the three studies, ActivitySpot evaluators used a pervasive computing system without previous training or even previous awareness of it. The first contact with ActivitySpot was generally made after reading advertisements spread throughout the physical space where the activities were available, mainly near the interaction devices. These advertisements contained short instructions about registration and device usage. Due to this approach of not personally inviting people to use the system, we had relatively few users when compared to the

universe of visitors in each scenario. However, we believe that this contributed to preserve the realism of the visiting scenario.

All evaluators responded a survey, composed mainly of 4-point Likert scale answers (1 – totally disagree – to 4 – totally agree). We opted for an even number of possible answers, so that we could reduce ambiguity and make participants definitely adopt a position instead of hiding themselves within an intermediary, uncommitted answer. In order to simplify the presentation and analysis of results, we aggregated responses into two categories: positive answers, i.e., meeting our evaluation goals, and negative answers. We consider that a particular goal is met when the number of positive answers is above the third quartile. The statistical significance of our results was assessed by a Chi-square test attempting to reject, for each question, the null hypothesis that positive and negative answers had equal proportions, with at least a 95% confidence interval. We next describe the results for each evaluation goal, mentioning the proportion of positive answers and respective Chi-square results², and conclude the section with complementary remarks.

1) *Compatibility of the conceptual model*: In all the three studies, participants clearly understood the assistance that was being offered to their activity. This result was particularly expressive in the last two studies (96% and 100% respectively, $\rho < 0.005$). It also appears evident to participants that all interactions were integrated into their activity (100%, $\rho < 0.005$, in the cultural center study, and 100%, in the conference study). We had trouble in evaluating the compatibility of the conceptual model of the provided assistance with the participants' mental model of the same activity, because our scenarios offered activity structures that visitors normally were not used to deal with. For example, when someone goes to the cultural center, he or she is not used to vote for a show, publish a comment, or share a photograph. In the poster session and cultural center studies, an activity analysis prior to the system implementation would not be of much value, because these are very simple activities. Evaluating this type of pervasive computing systems in a real scenario that totally meets the evaluation requirements is very difficult. Visitors are offered actions that, though being interesting and useful, are not part of the everyday structure of the particular activity. It seems that work activities are more suitable to achieve conceptual compatibility, as is the case of the conference study, where proposed actions were more compatible with the conventional conference activity structure (82%, $\rho < 0.05$).

2) *User interaction*: Our choice of grounding user interaction on basic, everyday interaction devices seems suitable to a walk-up-and-use pervasive computing systems such as ActivitySpot. Given their previous experience in using SMS, RFID cards, or public displays, participants had no trouble in using ActivitySpot without previous training, particularly using SMS and RFID (both near or equal to 100%, $\rho < 0.005$). Furthermore, participants generally were satisfied with the

provided usage instructions, even if we wrote it very concisely, and did not find the initialization procedure (at the registration desk) cumbersome.

Regarding predictability and response time, participants of the last two studies were satisfied (respectively 96%, $\rho < 0.005$ and 75%). In the poster session study, we could not evaluate this issue, due to technical problems.

Finally, all participants considered that using a system like ActivitySpot does not distract them from the activity they are carrying out (96%, $\rho < 0.005$ in the cultural center study and 88% in the conference one).

3) *Usefulness*: We adopted different evaluation strategies in each study for this issue. In the first two studies, we inquired participants for their general satisfaction regarding the system. Participants were generally satisfied with their experience (86%, $\rho < 0.01$ for the poster session study, and 88%, $\rho < 0.005$, for the cultural center one) and considered it more interesting than if it was carried out without system support (87%, $\rho < 0.005$, for the poster session study, and 88%, $\rho < 0.005$, for the cultural center one).

In the conference study, we introduced a control group, that was used to compare satisfaction regarding goal completion between system users and non-users. However, due to low participation at the conference and low response rate, we could not collect enough responses from the control group to obtain statistical significance. Therefore, we restricted usefulness evaluation in this study to the experimental group. Results showed that participants considered that the system support helped them in achieving the goals for their activity (75%), and that it was more effective than if it was provided over a single application on a mobile phone (82%, $\rho < 0.05$) or an interactive kiosk (91%, $\rho < 0.01$). However, participants interestingly stated that they could perfectly achieve their goals without ActivitySpot or any other computer system support (87%).

In all the three studies, all participants recognized that the system was providing them with personalized information (88%, $\rho < 0.005$, for the cultural center study, and 75% for the conference one). However, the same participants considered that for personalization to be more useful, the system should have access to more personal data (100%, $\rho < 0.005$, for the poster session study, and about two thirds for the other two studies). This is an expected consequence of the current lack of solutions for the seamless integration between the local infrastructure and the personal domain.

4) *Closing remarks*: This series of user studies has allowed us to demonstrate that visitors to public spaces can easily understand the type of activity-centered support provided by ActivitySpot and that they do not find obstacles in using the provided interaction means for carrying out their activity. Previous experience in using the basic interaction devices on which ActivitySpot is grounded was fundamental for these results. However, it is not always possible to provide an activity model compatible with the visitors mental model, due to the nature of the activity itself, which, with the introduction of pervasive computing support, may become somehow artificial.

²When no ρ value is provided, this means that we could not reject the null hypothesis, though this could in most cases be achieved with a larger sample.

This, along with the more or less compelling assistance that may be provided, which does not depend on the ActivitySpot infrastructure, may affect usefulness of the system. As noted by Edwards et al [22], infrastructures can only be evaluated in the context of use and thus must be evaluated indirectly through applications built on top of it, thus incurring in the risks of supporting unattractive applications or getting distracted by the demands of application development and to lose sight of the real purpose of the effort, which is purely to evaluate the infrastructure. Finally, usefulness is also influenced by the current lack of mechanisms for automatic integration between the local infrastructure and the visitors' domain, key to providing more effective personalization.

System usage log analysis and some observations allowed us to obtain some additional intriguing results:

- Participants tended to interact predominantly with the public displays, mainly with RFID tags (half of the interactions in the cultural center study and more than 75% in the conference study), probably due to ease of use and immediacy of response.
- Even though the lower SMS habits of our population sample (around the 30s) when compared with younger individuals may have influenced their cost perception, some participants complained about the cost of SMS usage, which ultimately results in a barrier to usage.
- The importance of entertainment and engagement in this kind of system, reflected by the notorious pleasure that some participants demonstrated when sharing their own photographs with the system and watching them being displayed in the big size screens to all other people.

Besides the end-user evaluation, these user studies also allowed us to demonstrate different technical capabilities provided by the ActivitySpot infrastructure, such as the simultaneous support to different users and activities, coordination and integration of heterogeneous interaction means into the same activity, action and operation reuse respectively in different activities and actions, usage of the same interaction means for different actions, and explicit and implicit activity initialization. Though targeted at distributed interaction with pervasive computing devices, the ActivitySpot infrastructure was also employed in the first two scenarios to support Web interaction as an after-activity complement. It just required a simple HTTP gateway that converted HTTP requests and responses into ActivitySpot stimuli and responses.

VI. RELATED WORK

Project Aura [4] implements the concept of task-driven computing by capturing user intent and mapping it into a task corresponding to a set of abstract services, which are further concretized by the environment infrastructure providing continuous support to user tasks regardless of the environment in which the user is. The Aura of each user represents the set of services required to accomplish a task or activity and allows the user to move from environment to environment while keeping the task in execution with the resources available in that environment.

Christensen and Bardram [3] also grounded on Activity Theory to develop a pervasive computing system (the ABC platform) supporting collaborative activities within health-care environments. Their effort is centered on environments where users are well-known (e.g., hospital staff). Like Aura, user activities are described as an abstract composition of applications which are instantiated in each environment where the user goes to (e.g., a display in a patient's room).

Our work differs from these activity-centered approaches in the way human activity is associated with the dimensions of space and time. While our work is focused on different activities performed simultaneously by multiple people in a specific physical environment within a rather short period of time, theirs is targeted at the migration of user activities between different environments and along an unbounded time boundary.

Our work also relates to a number of projects based on scenarios where pervasive computing supports occasional visitors to public spaces. Exploratorium [23], Sotto Voce [24], and GUIDE [25] are examples of such projects. All these projects are based on some sort of electronic guidebook running on a PDA or a tablet PC, where users look for information related to the physical environment they are visiting. Although system functionality was organized around common visitor tasks, none of these projects adopted an activity-centered approach. The approach was rather application-centered, specially in the case of GUIDE, expecting from users to browse through the application in order to execute some location-dependent task. In the case of Exploratorium and Sotto Voce, although relying as well on a single application, the focus was much more on location, with different information being accessible to visitors as they roamed all over the space. Furthermore, unlike these projects, ActivitySpot does not require interaction with a specific device, but rather explores basic, heterogeneous interaction means that do not require previous training because of their generalized usage, which is definitely an advantage for visitors.

Finally, ActivitySpot shares with Gaia [26] and Interactive Workspaces [27] the objective of providing a generic computational infrastructure for pervasive computing. Both infrastructures also provide their own abstractions for modelling user interaction as well as easing the task of application developers. What distinguishes ActivitySpot from these infrastructures is its activity-centered approach, which is reflected on the software architecture and on the way developers build applications.

VII. CONCLUSIONS

This paper presented a conceptual model for localized activities and user interaction in pervasive computing environments, as well as its implementation – the ActivitySpot infrastructure. This work is based on an activity-centered approach for system design, which becomes especially important in situations in which people have little or no prior knowledge about the physical environment or about the activity they are going to perform. The main contributions of this work are the

Activity Theory-inspired conceptual model and a software infrastructure, derived from this model, providing a generic tool set and a runtime environment for pervasive computing support to localized activities. The interaction model proposed by ActivitySpot is based on simple, everyday interaction devices, which facilitates usage learning, a particularly critical feature in walk-up-and-use scenarios such as those considered in this work. Furthermore, by not restricting user interaction to a limited set of devices, ActivitySpot can be used by a wide, potentially unlimited user population.

Our proposed conceptual model was evaluated by user studies run in different public spaces. Data collected from the studies showed evidence of the suitability of our interaction model. Visitors perceive such an approach as a natural one and, since it is based on simple interaction mechanisms, they generally do not find problems in using applications developed on top of ActivitySpot. However, like it happens with any other infrastructure, its success depends heavily on applications and on the way they are presented to users. In the case of visitor assistance in public spaces, this dependence is stronger, because visitors have to be attracted; there must be a strong appeal, something that makes visitors believe that it is worth trying a new way of performing their activity.

The results here presented do not completely validate the ActivitySpot framework, because the evaluation will not be complete until we assess the developer and administrator perspectives, i.e., how ActivitySpot is effective in improving the job of public space staff managing a pervasive computing infrastructure that assists visitors as well as easing the job of pervasive computing developers in writing the support to new actions. Current work is now focused on developing and evaluating higher-level tools and APIs for ActivitySpot administration and development.

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