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Abstract. This paper provides a snapshot of the BlueSpace project at the IBM T. J. Watson Research Center. The goal of BlueSpace is to research the issues associated with next-generation workspaces in which integrated electronic transducers, displays and network appliances are used to augment personalization and context awareness. Toward this goal, we have constructed a full-scale prototype office and implemented several applications, which include situation-triggered environmental adjustments and context-aware event notification. These applications use a set of infrastructure services based on document technology (XML) for sharing contextual information. The prototype is viewed as a sandbox to which additional technologies and interesting applications can be added and evaluated in the future.

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Introduction

Since the late 1980s companies in the United States have been moving towards creating a more flexible and collaborative workplace to respond to the dynamic demands of the business environment. Adaptable workspaces are viewed as having the potential to speed information flow, facilitate spontaneous team interactions, and support business processes [9][27]. An important trend is the use of open-plan offices where workers are no longer confined to private rooms, but instead inhabit semi-walled areas commonly known as cubicles. As offices evolve from rigid, closed environments into flexible, open spaces, individual comfort and privacy become of greater concern. The corporate goal of achieving economies of scale and space through the installation of uniform cubicles can occasionally overshadow employees' needs for individuality and quiet concentration. Studies have shown a measurable impact on productivity due to environmental factors such as temperature settings and noise levels [14][20][29][30]. Providing the appropriate level of thermal comfort, air quality, and privacy for an individual can result in improvements in productivity as well as higher employee moral and retention.

At the same time, many companies are using alternative workplace strategies including *virtual officing* and *hoteling* [9][26]. According to this view, offices no longer need to be dedicated to specific individuals but can be assigned to employees based on the dynamically changing needs of the workplace. Armed with an array of technological tools, employees can work anywhere, anytime [3]. However, coming to office provides workers the added value of interacting with colleagues and facility support beyond what alternative workspaces provide. For knowledge workers, the most valuable asset of any business and estimated to account for 75% of the United States office population [27], it is even more important to provide an environment that promotes open communication and minimizes unwanted interruptions and distractions. Steelcase's Personal Harbor® [4] is an example of office design that allows occupants to quickly transform their space from one that maximizes individual privacy to one that supports group collaboration.

In addition to changing the physical environment, changing the way technology is used can play a crucial role in workplace productivity. Most knowledge workers are heavily dependent on the use of technology to accomplish their daily tasks. It is paramount to allow workers to focus on accomplishing the task at hand without needing to deal with the complexities associated with the introduction of new technologies. Research in technology-integrated workspaces has been primarily focused on the capture, display, and sharing of information for team collaboration. For example, Raskar *et al* [24], describe a futuristic office using a combination of cameras and projectors for recording surface information from office objects and displaying images on designated surfaces. The Interactive Workspaces Project (IWP) at Stanford [25][15] explores new ways for people to work together with interaction devices on many different scales, from PDAs to large wall-mounted displays.

The research described in this paper relates to general efforts of the scientific community towards ubiquitous computing [28][1]. It also relates to intelligent environment

research addressing other types of spaces, such as the home [7][17], classrooms [2], and children bedrooms [6]. The project was a collaboration between researchers at the IBM T.J. Watson Research Center and the Steelcase research organization. The Steelcase researchers brought to the table a wealth of knowledge and first-hand experience of workplace issues, as well as expertise in office furniture design.

In the first section of this paper we discuss current issues in office environments and motivations for several of the solutions that we implemented. Next, we describe the BlueSpace prototype environment, including the applications, devices and services implemented to date. We then provide an overview of the underlying software infrastructure, describing its programming, run-time operation, and other issues important in deploying such an infrastructure throughout an enterprise. Finally, we provide a discussion of possible future research.

Workplace Issues and Goals

As part of our research on the BlueSpace project, current workplace issues and goals were examined through a series of interviews and focus groups with people from a variety of function areas (e.g. marketing, development) and a range of company types (e.g. large corporations and dot-com startups). In total, 50 people were interviewed from six companies in either a small group or private setting.

While it was already clear to us from prior research that temperature issues (too hot/too cold) combined with ambient noise levels could impact occupant productivity, we wanted to explore how users would prioritize their needs in a perfect world. While the interviews were focused on understanding individual work environments and contained typical questions for this task (e.g. "what do you like best about your current office space"?) the focus groups were conducted later in the development cycle. This allowed us to show participants a first model of the proposed prototype. Feedback was solicited on the model, and a prioritized feature set was created through discussions and brainstorming.

In discussions of the constraints created by the current work environment, users mentioned the need to search out conference rooms even when the collaborative work involved only two or three people. Conference rooms are usually a scarce commodity and meetings in them require organized planning to reserve the space. This planning step often prevents spontaneous work groups from occurring, or requires that people wander the halls in search of an empty room to work in. The preference would have been to continue the collaborative work in the workspace where it had its genesis, but "two people working around a screen is difficult, with three people it becomes impossible." Thus it became clear that task demands occasionally drove office occupants out in search of other spaces because the task could not be accomplished within the confines of the individual workspace.

In addition to collaborative work, other reasons mentioned for leaving the cubicle included managers seeking privacy to make a call or conduct a one-on-one review, and a desire to prevent disruption to surrounding cubicles when using a speaker phone. Many participants who work in open-plan settings also mentioned the need to "find a quiet space"

to do heads-down work without interruptions and distractions. While some went to an enclave (i.e. a one-person conference room), most felt the need to do their quiet work either at home or in the office during off- hours (either late at night or early in the morning). The major drawback to working in an enclave is that users invariable found that they had forgotten to bring something they needed to get the task done. Many commented they are reluctant to leave their primary workspace since they usually do not have a network connection in the alternate workspace and they worry about being out of touch with their email (in addition to being away from voicemail). The overall goal when trying to accomplish work that requires greater concentration was to minimize the number of "drive-by interruptions." These are instances where a colleague is walking by and remembers when he sees you that there was something he wanted to ask you, or just stops in to inquire about your weekend or because he needs a recommendation for a local restaurant that serves Thai food.

The need for "privacy on demand" emerged from these discussions. This represents the ability to have the space be as open as necessary to support group interactions (open between adjoining workspaces and between the workspace and adjacent common space) as well as the ability to close the space up so that both visual and auditory privacy are possible. Users were also seeking the technology equivalent to a "cone of silence" that could descend upon their workspace and prevent unwanted interruptions. Lastly, greater individual control over environmental issues that impact personal comfort was requested. While most have adapted their dress code to deal with too hot/too cold issues (some wear a sweater, others opt for short sleeved T-shirts) it was perhaps the need to conform that chafed more than the outcome. Many mentioned wishing for the "comforts of home" in a setting where a greater number of waking hours was spent than at home.

Overview of BlueSpace

Figure 1 shows the current BlueSpace prototype. The workspace occupies an 9' by 10' footprint in the lab and incorporates a set of sensors (too small to be seen in the picture), for measuring ambient lighting, temperature, humidity, and noise level. An active badge reader is used for presence detection and identification. The desk chair is equipped with a pressure sensor connected to a wireless micro-controller, which detects if a person is sitting in the chair. A set of environmental effectors has also been integrated into the overall system, including various illuminating and signaling lights and a Personal Environmental Module (PEM) [5]. A PEM is composed of a fan system and a heat panel, designed to provide adjustable heat and airflow to desks in open-plan offices. The module is installed at the bottom of the main desk, as indicated in Fig. 1.
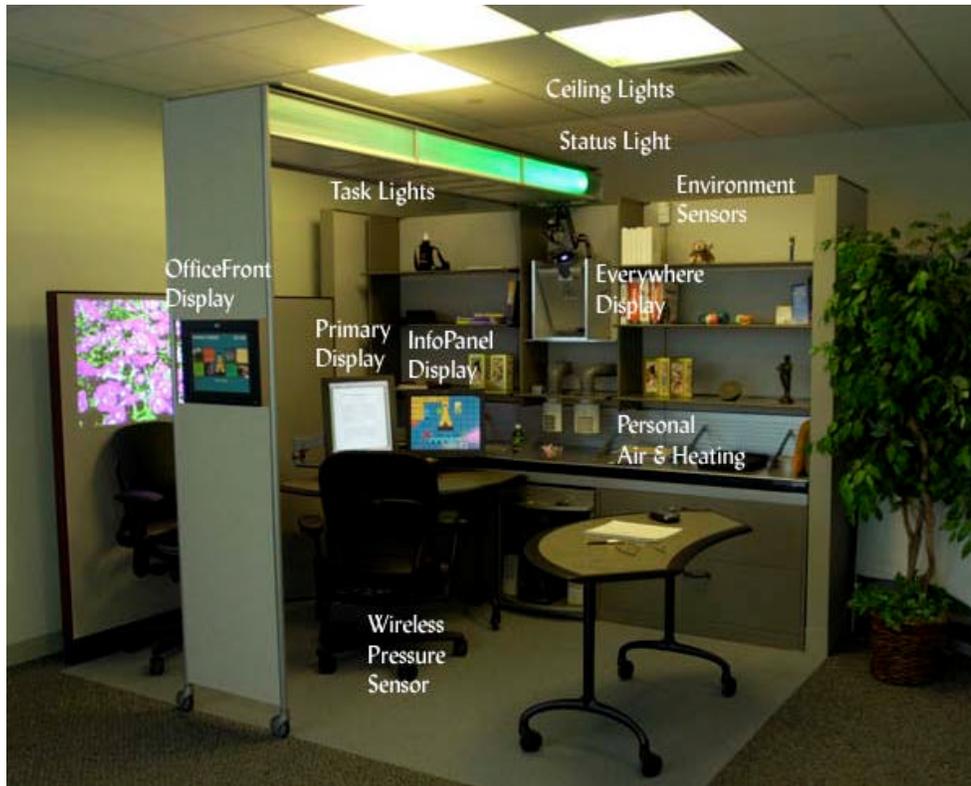
Figure 1. BlueSpace prototype workspace.

The sensors and devices are connected to a *workspace appliance* (not shown), using a combination of serial bus, LonWorks network [13], Ethernet, and Bluetooth. The workspace appliance acts as a server for the space, providing infrastructure services and an integration point for the transducers. Its role is described in greater detail in the Software Infrastructure section.

There are three flat panel displays in the space. The first is next to the workspace entrance and is used for sharing information about the occupant such as his current availability. The two other displays (the Primary Display and Information Panel) are mounted with articulating arms. These are for task-oriented work and information at a glance. In additional to the three fixed displays, there is a steerable projection system we call the Everywhere Display projector (ED-projector) [22]. It uses a computer-controlled mirror to direct projected images that have been corrected for keystone distortion onto virtually any surface in the workspace. The ED-projector (shown in detail in Fig. 2) is installed in the middle of the back wall of BlueSpace, close to the ceiling, to maximize area coverage and reduce obstruction. The use of

Figure 2. The Everywhere Display

ED in the workspace has many interesting potential implications, from personalizing the environment to liberating the user from the confines of the desktop display, as discussed in the next section.

User Functions and Applications

Two of the main objectives that we sought to address from a user's point of view are personalization and the ability to easily configure both the workspace and the technology for either collaborative or quiet individual work. The following sections highlight our efforts in these two areas.

Workspace Personalization

BlueSpace provides computer control over the lighting and temperature conditions of the physical environment, empowering the office worker to personalize his workspace

Figure 3. The Information Panel.

based on the current task, and how he feels at the moment. Additionally, the space can sense and automatically adjust the environment based on the current context and user preferences. Lighting and temperature are easily adjusted through controls provided on a touch screen display. The Personal Environmental Module provides fine-tuning of local temperature by controlling both temperature and speed of airflow, as well as radiant heat. The fluorescent ceiling lights can be dimmed and the task light can be adjusted for any color in the spectrum as well as dimmed. This allows the occupant to simulate a broad range of lighting effects ranging from the warm appearance of natural sunlight to cold florescent lights.

The environment controls are currently on the Information Panel (figure 3). This interface was designed to provide easy control of frequently used devices and quick access to information. Sensor outputs, for example, are displayed there providing the current office temperature, humidity, ambient light and noise levels. The occupant can easily customize the Information Panel to show his calendar entries for the day, a to-do list, webcam images and other items that they use frequently or would like to view directly. In

addition, presets and preferences can be established giving the user the ability to quickly re-configure the office lighting with the touch of a button.

The Office Front display (figure 4a), mounted near the office threshold, allows the user to add a personal touch to his workspace that can be viewed by people walking by. This display can be customized to include favorite images as well as text describing work

Figure 4. a. The Office Front display (left) and b. the computer work area (right).

activities and other interests. Figure 4b illustrates the occupant's workstation area that includes the Primary Display on the left, the Information Panel in the center and a movable display, which in this example is projected to his right. To maximize their viewing comfort users can easily adjust the position and orientation of these displays. The ED-projector display can be moved to any surface in the room.

Instead a display, the ED-projector can be used to project a favorite image to create a personal feel to the workspace. Figure 5 shows how an empty space of the office is transformed by the projection of artwork, or used to mimic a window by displaying images taken by an outdoors webcam. In our prototype, the ED-projector defaults to one of these options whenever it is not employed by the user as an extra computer display.

Figure 5 . Wall mural and virtual window.

BlueSpace uses context awareness to automatically reconfigure and effectively manage the workspace. For example, upon arrival in the morning, the active badge system reports the presence and identity of the individual entering the empty office. The system, continuously aware of the office context, confirms the occupant is the workspace owner,

looks up her preferences for lighting, temperature, decoration, etc. and automatically configures the workspace to these preferences. Conversely, upon departure at the end of the day the workspace is automatically configured to its preset nighttime settings.

We are also exploring the use of the noise level detection to avoid situations where the occupant's behavior disrupts the work of nearby offices. Our basic approach is to use a mechanism that warns the worker if noise levels exceed a pre-determined threshold.

The features of BlueSpace described above combine to provide a comfortable workspace that the occupant can configure based on personal preferences. In addition, context awareness and automation ease interaction with the environment. This approach could be easily applied to the case of hoteling. The workspace would automatically be reconfigured based on the current occupant's preferences, creating a sense of familiarity even in spaces never occupied before.

The Privacy/Interaction Continuum

A second functional objective in BlueSpace is to support users' need for privacy when performing tasks that require concentration or discretion as well as their need to work collaboratively with colleagues. These needs can be viewed as opposite ends of the same continuum and require a set of protocols and tools to flexibly manage them throughout a workday. We have developed a set of functions to support this privacy/interaction continuum.

The cornerstone of our approach to privacy is the management and awareness of an individual's status.

An individual can set his status at the touch of a button to one of the following values: Free, Busy, Gone, Be back, Lunch, Coffee or Hidden. Our active badge system is used to automatically detect several of these states. Specifically, it automatically changes from "Gone" to "Free" when the occupant first arrives in the office and back to "Gone" at the end of the day, upon detection that the occupant has left. The user can optionally write an informative message that elaborates upon the status. For example, the "Be back" status may be accompanied by the message "I'm in Hawthorne, back at 3:00pm."

This status information is distributed and presented throughout the workplace in a variety of ways. First it is clearly posted on the Office Front panel. To allow for easy determination of basic status, we incorporated a colored Status Light, installed on the top beam of the front of the office (see Fig. 1, top-right). The Status Light color is used to indicate the individual's status (Free=green, Busy=red or Gone=blue). Co-workers can easily determine the working status of anyone in the office by just checking the Status Light, even from considerable distance. The hope is to deter "drive-by interruptions".

In addition, we have developed a Buddy List application for the Information Panel that allows users to view the status of selected colleagues at-a-glance. An interesting feature of the Buddy List application is that one can opt to "Wait" for a colleague that is currently "Busy." When the "Busy" individual becomes "Free" the person waiting is immediately notified of this change. The Buddy List of an individual that is "Busy" indicates the identity of any co-worker that is waiting for her. This way, a worker can easily check whether there are people waiting to work with her, and try to make herself available.

Another key function that we are developing is the ability to support context-aware notification. Notification events are triggered by a change in the state of the environment. An example of a notification scenario is the arrival of email. The goal is to enable a worker to concentrate on the work at hand, but still allow notification of important events. If the occupant has set his status to "Busy" he is only notified of urgent email. In this situation, the notification is trimmed to display only the sender, subject and a summary of the message. If the occupant is "Free", he receives all notifications (e.g. email, reminders). More interestingly, the notification is projected on the panel at the occupant's current location using the ED-projector. The location can be inferred from the pressure sensor imbedded in the chair he is   sitting on. Figure 6a illustrates the ease with which the user can glance at the notification and return to work. However, if the user is in the office but not in his chair, the notification is projected on the wall, where there is a greater chance for
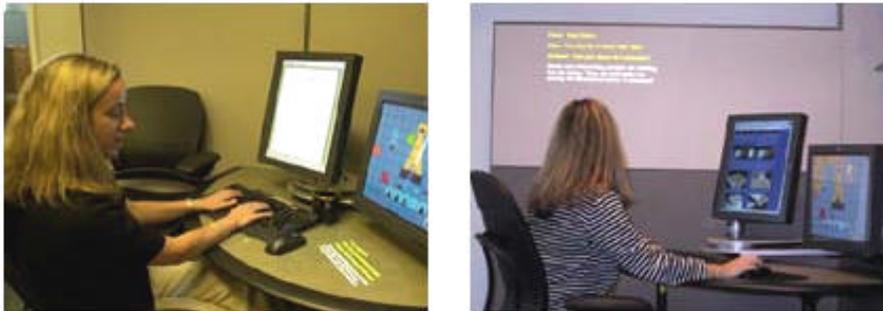

Figure 6. E-mail notification when seated at the computer and when elsewhere in the room.

it to be seen. To help the user detect that a notification has arrived, an optional audio indication can be added. The audio event is   translated to a short series blinking lights if BlueSpace detects that the occupant has set his status to "Busy". Of course, if the worker is not in the office, no message at all is displayed.

BlueSpace also monitors the presence of other active badges in the workspace and automatically reconfigures itself when a visitor is detected. When a visitor enters an occupied space, confidential or private information currently displayed on the Information Panel, such as calendar and to-do's, is immediately hidden, preserving the privacy of the office owner. The personal wall mural displayed is also toggled to a "public" mural, maybe with a less personal motif or based on company regulations. Similarly, in the case of the notification scenario described above, the projected image only mentions that urgent e-mail has arrived, hiding the sender, subject, and summary.

A problem mentioned in the focus groups is the difficulty of working collaboratively in the individual's workspace. We are tackling this problem by incorporating applications and devices in BlueSpace that facilitate teamwork of 2-3 people. In particular, we are using the ED-projector to allow collaboration without the "two people working on the same screen" problem. The ED-projector easily transforms any wall into a display, as shown in Fig. 7a.

However, other types of work may require the users to sit around a table while working with the computer. Figure 7b illustrates how the ED-projector can bring the work being discussed to the top of the table. Notice that the projected image is just the normal desktop display of a computer, easily allowing interaction through the use of wireless mouse and

Figure 7. The Everywhere Display projecting information on a wall (a) and on a table (b).

keyboard. Eventually this interaction may occur simply by hand gestures such as pointing and clicking, detected by a camera using computer vision techniques [22].

BlueSpace provides remote access to all workspace functions by virtue of its web-based implementation. A user can access all the functions through any web-browser that supports DHTML. For example, one can change his status or view the status of other colleagues using a Pocket PC via a wireless link.

The Software Infrastructure

This section describes the middleware that makes the overall BlueSpace environment work. The BlueSpace middleware has essentially four functions. First, it provides support for representing context information via open-standard document technology. This includes measurements, messages, commands and other environmental information. Second, BlueSpace middleware provides a shared information space where devices and applications in the environment can publish information. Third, it manages active information such as events, state changes and notifications through an event subscription service. Lastly the middleware generates interactions, which use the devices, displays, and other agents in the environment to interact with the human user. This section will discuss each of these four functions in detail.

Representing Context Information using Document Technology

A key goal in the design of the BlueSpace software infrastructure is to provide an environment that scales as it is deployed throughout the enterprise. We believe that the infrastructure for physical environments should seamlessly become an integral part of an overall information technology infrastructure, and in particular, an integral part of a wide-ranging network infrastructure. Toward this goal, the BlueSpace software infrastructure builds upon and extends key next-generation Internet technologies. Document technology (specifically, XML, XPATH, XSLT, HTTP, and SOAP) provides a uniform paradigm both for communication and for programming. For communication, documents are used to represent events and state. Event and state documents encompass all information that is sensed or gathered in the environment. This ranges from running measurements (*e.g.* "the current ambient temperature is 71F"), low level device events (*e.g.* "the motion sensor has been triggered") to higher level interpretations of user gestures (*e.g.* "the user has selected an icon"). Documents are also used to represent commands and interactions. Command and interaction documents encompass all information that causes physical and logical changes in the environment. These documents can range from low-level device instructions (*e.g.* "turn the task light on") to higher-level representations of complete user interfaces (an HTML page and data set).

Document technology also provides the basis of several key elements of programming in the BlueSpace environment. A document-oriented approach is used to arrange the information space for the environment. It is also used to make associations between event conditions and the appropriate responses to those conditions. Lastly, it is used to generate and manage complete interactions that provide a uniform experience for the human user in the environment.

Hierarchical Arrangement of Context, State, and Event Information

BlueSpace provides a mechanism, called a "context distribution service" for storing and retrieving context information. This service is used by the various devices and agents in the environment to share and distribute states, events and other information. The context distribution service operates like an information blackboard. It provides a way of naming an item of information, submitting it to the service ("publishing it"), and then sharing that information by retrieving it using the name.

The context distribution service arranges information hierarchically, rather than as a flat space of names or tuples. This is similar to a hierarchical file system, which provides a hierarchy of directories for publishing individual units of information ("files"). The difference being that the context distribution service publishes sets of documents rather than sets of files.

The following XML fragment gives an example of such a structure, representing the elements of a single electronic office.

```
<Floor id="LDB4W">
```

```
<ElectronicOffice id="4030">

  <states>
    <ActiveBadgeState/> …
    <PresenceState/>
      <Occupant present="true"/>
      <Visitors present="true">
        <Visitor>Tony</Visitor>
      </Visitors>
    </PresenceState>
  </states>

  <devices>
    <TaskLight/>
    <OfficeLight/>
    <Heater/>
  </devices>

  <displays>
    <InformationPanel/>
    <EveryWhereDisplay/>
    <OfficeFrontPanel/>
    <Desktop/>
  </displays>

</ElectronicOffice>
…
</Floor>
```

This is a sample information space for a single office. It is itself an XML document, with each element of the document representing a location at which information can be published. For example, a document representing the condition of a radio-frequency "active" badge reader would be published to the location given by the `<ActiveBadgeState>` element.

This hierarchical structure has several advantages over a traditional tuplespace, which has a simple, flat structure [18]. The hierarchy allows a fine level of discrimination over the various elements -- devices, sensors, effectors, and displays -- in the environment. It also supports the presence of any number of different elements of the same type. Additionally, it provides sufficient representational power to scale beyond a single environment -- for example, a large enterprise in which *many* electronic offices must be managed. Note that individual environments could be hierarchically structured into aisles, floors, buildings, and organizations.

The hierarchical structure is itself based upon XML, and is structurally isomorphic to an XML document. The runtime structure is, in fact, an instance of a W3C compliant document object model (DOM) data structure. Note also that the state of the environment can be easily saved as a passivated DOM (a XML file).

In general, the results published to the context distribution service form a current model of the overall office environment, which may comprise user activities, environmental conditions such as temperature, system configurations and many more types of information. Within a single office it gives programmers the ability to organize the

different events and sensor data into categories, which can lead to more understandable code. However, it can also improve system performance by restricting queries to the necessary directories. The context distribution service is highly programmable, providing both procedural and messaging interfaces for accessing and manipulating information in the hierarchical store. These interfaces enable a wide variety of overall configurations of the infrastructure.

The interfaces may be used directly, by procedural code that runs in the same address space as the service. This form of approach is useful for configurations where the devices, sensors and other elements of the environment are to be controlled in a single locus of control, for example, by a workspace appliance. The interfaces may also be accessed via a messaging service, based on the exchange of XML documents over HTTP connections (the current implementation runs directly against HTTP and is being migrated to SOAP). This form of access is useful both for remote clients and for remote administrative applications. It is also possible to use the interfaces in a mixed mode, in which there is a combination of local (direct) and remote (messaging) access. We have implemented our prototype environment in this fashion. In that environment, which manages a single electronic office, control is centralized in a single process that implements an information space similar to the example above. Most of the device controllers and actuators in this environment are deployed in the same address space as the central control process. The client applications described above, including the Information Panel, the Office-Front display, and the Everywhere Display, use the messaging interface, and communicate by sending and receiving XML messages via an HTTP connection. Note that even these applications that run in the same physical vicinity of the environment may be structured to use the messaging interface, and would appear to be remote access clients. Finally, we have implemented a longer-range remote client, which runs on a PocketPC handheld computer. Note that this client can access the office environment from any location, yet would appear as another application using the messaging interface.

Using Expressions for Query and Subscription

BlueSpace provides a mechanism for accessing the shared information in this hierarchy via expression-based queries and subscriptions. Consistent with our design goal of building upon and extending key Internet technologies, the subscription and query service is based on the use of XPath expressions, which is a standardized W3C specification for searching elements, nodes and attributes in XML documents.

The use of expressions to access information in the environment can be quite simple, and in its basic form, maps into other context storage strategies that represent information using a flat, tuple-oriented naming space. For example, to locate a document providing the state of the active badge device in the sample context space described above, the simple expression: ActiveBadgeState would suffice to locate the information. Of course, a much more precise specification of the desired information is also possible. For example, the expression

```
Floor[@id='LDB4W']/ElectronicOffice[@id='4030']/states/ActiveBadgeState
```

would locate a particular active badge document, within a particular office within a particular floor within a larger physical environment. Note also that information about the environment could be found using wildcards at various levels. For example,

```
//*/ElectronicOffice[@id='4030']/states/*
```

would return all information about state-collecting devices in office 4030.

BlueSpace also provides support for expression-based subscriptions. A subscription is a registered query expression that identifies one or more locations in the BlueSpace context distribution service which a subscribing agent, called a listener, wishes to monitor. BlueSpace supports subscriptions by storing one or more document expressions that describe the locations and conditions that a listener wishes to monitor for changes, or for the arrival of events.

By using the subscription mechanism, a listener could essentially monitor changes in the state of a variety of devices or other agents in the environment. Because of the unrestricted nature of the naming of hierarchies and locations in the BlueSpace infrastructure, it is possible for application and device authors to develop their own conventions around how to rendezvous around the state and event publication process.

A particularly useful technique are rendezvous strategies which convert low level information into high level information For example, in the sample environment above, a special identification agent could be used to identifying humans arriving and departing the physical environment. Such an agent would use the subscription facility to register itself as a low-level listener of active badge activity within the environment. This listener would subscribe using an expression as above. Upon receiving events from a badge reader, the agent would retrieve the technical data from the active badge event that has been published. Then the agent would perform a database lookup to identify the human user. Next, the identification agent acts as a publisher, as well as a subscriber. Upon identifying the human against the active badge, the (higher level) human identity is published to an appropriate location. Thereafter, the higher level information, which represents the presence of human users (or visitors) could be itself subscribed to by other agents. For example, the subscription expression

```
PresenceState[Occupant/@present='true']/Visitors/Visitor[.='Tony']
```

would provide an appropriate notification whenever a specific visitor. In this case someone named "Tony" has arrived at the environment.

BlueSpace also provides both programmatic (direct) interfaces as well as messaging interfaces for registering and de-registering subscriptions, for identifying listeners, and for the delivery of subscribed information (e.g. the events). BlueSpace provides various forms of subscription registration that support a high degree of detail about the various conditions under which the subscription should be activated and what information should be delivered to the listener.

Generating and Managing Interactions with the User

The BlueSpace software infrastructure provides an additional facility, called an *interaction service*, for programming and managing interactions with a human user. An

interaction is essentially a document that is sent to any of the devices, actuators, or displays in the environment, and which causes information to be sent to the user and/or collected from the user. This section discusses three key functions of the interaction service.

The first function of the interaction service is to cause data and other raw information to be gathered from the environment for use by the human user. This information can come from events or state documents in the environment, from other data sources, or from information downloaded from network URLs or SOAP calls.

Consider the occupant arrival scenario described in the sample application discussed above. There, a combination of low level and high level device agents have determined (from an active badge stimulus) that a certain human user has entered the environment. A useful interaction at this point would be for the environment to challenge the human to log into the system in some way. In this case the interaction service would collect the user id and the location as two data items which are to be used as input to the interaction.

The second function of the interaction service is to cause information to be customized into a form that may be displayed, rendered, or otherwise transmitted to the human. This is accomplished through the use of transformations, which are programmatic elements that convert one document form into another. The interaction service selects transformations based upon rules that describe conditions in the environment, user preferences, and device capabilities. This allows wide variety of generated forms of an interaction, as appropriate for the environment.

Returning to the sample application, this means that the inputs to the interaction, the user identifier and location, must be rendered to the human, and additionally, it must be made clear to the human that a password is expected in return. Thus, the interaction must result in an interface being generated, in an appropriate renderable form, and presented to the user on an appropriate device. An example is the following:

```
<html>
  <head>
    <title>Please Login to BlueSpace Environment //LDB4W/4030</title>
  </head>

  Please Login to BlueSpace Environment //LDB4W/4030

  <form action="…">
    <input name="userid"   type="text">John Doe</input>
    <input name="password" type="password"></input>
  </form>

  Otherwise we will release the hounds.

</html>
```

The third function of the interaction service has to do with the mapping and binding of data. This process causes the input information to be bound to the rendered interaction form, making it viewable in most cases. Once the interaction is complete (e.g. the OK button is clicked) to extract the output data from the interaction and return it to the environment.

In the sample application, this means that the input values, the user identifier ("`John Doe`") and the office location ("`//LDB4W/4030`"), are placed into the display. Upon the appropriate completion conditions, the user identifier and password are collected and the display is retired. The collected data must be returned to a prescribed location in the storage. Note that the arrival of this information may itself be subscribed to, as per the previous section, and the successful challenge and login interaction would result in follow-up interactions (such as a welcome page being displayed, or perhaps the hounds being released).

Discussion and Future Work

The BlueSpace project is investigating multiple aspects of technology-rich work environments, with a near-term focus on addressing the needs of people in individual workspaces. The development of the initial BlueSpace prototype reported in this paper brought to light several interesting issues related to ubiquitous computing that merit additional research.

The first of these is in the area of the user experience. New interaction paradigms which take advantage of speech technologies and off-the-desktop display devices such as the Everywhere Displays projector support the move away from a desktop-centric approach to addressing office computing needs. In addition, we are currently furthering our research on interaction devices to enhance the user experience in the workplace. In particular, we are exploring different technologies to allow device-free user interaction with the displays created by the ED-projector. The goal is to allow user interaction with simple hand gestures such as pointing to the surface [10] and clicking, detected by a camera mounted close to the projector. In this configuration the ED-projector could be used to render any appropriate workspace surfaces into an interactive surface (subject to physical limitations such as occlusion and surface reflectance). Bringing this interactive capability to the physical surface where the user is actually conducting the task supports truly ubiquitous computing without the need of wiring the surfaces or putting marks on objects (like in [16]). Several of the challenges that need to be overcome to reach this goal include dynamically estimating surface characteristics and reliably capturing user input by means of analyzing hand motions on or near the surface.

Another area that we would like to explore further is how the occupant can communicate with the room. Currently, all interaction happens through the Information Panel. We are starting to explore the idea of using an avatar for the space: a personified manifestation for the software that assists the user in managing the workspace either while the office occupant is present or absent. In particular, we are considering the use of the avatar as a focal point for the user interaction. Manifestations such as these assist from a speech recognition point of view since often the user will turn towards the avatar to address it, facilitating directional microphone capture of the user input. Also, if speech commands are used for control of office appliances and environmental settings, the avatar provides a conversational partner for the user, thus eliminating the problem presented when users are required to "speak to the walls." The avatar could also play a social role, greeting visitors and taking messages when the office occupant is absent from his space.

Of course there is the more general question of whether users want to speak to an office or to its avatar. Recent research work has compared different modalities to control interactive spaces, such as speech, graphical displays, gestures, etc. [19][8], using a wizard of Oz approach. The results seem to be too preliminary to allow a definitive answer. We are planning to use BlueSpace as an environment where we can investigate such issues with real users in a true automated environment, without the burden of having the conduct wizard of Oz experiments.

Another issue that is central of our efforts is the detection of user's attention and its integration to the framework of context-awareness. We have created a prototype of workplace with multiple modalities of input and output, but we are still struggling to create productivity-enhancing mechanisms to select the appropriate modality for the delivery of messages and notifications. Part of the problem is related to the fact that the system does not know what the user is doing and to which activity she is attending. Unlike in living room spaces [7], tracking the position of the user in the workplace provides minimal information about her action and attention focus. We are currently investigating the possibilities of incorporating head- and eye-tracking devices (such as [21]).

On the infrastructure side, we continue to investigate architecture and component issues related to application development [11], run-time support, and enterprise deployment for smart spaces. For example, we are investigating the possibility of extending the context distribution service to allow subscriptions of situational or temporal events with XPath. The concept of situation, as described in [12], treats the states of related entities as a whole, is a powerful mechanism for reducing programming complexity. Similarly, actions triggered by temporal events such *as* "turn the light off 5 minutes after the occupant leaves the office" could be easily programmed if such events can be described and subscribed. However, to incorporate more complex temporal structure it will be necessary to explore richer programming paradigms such as the one discussed by Pinhanez in [23].

Infrastructure for supporting applications to exploit the input and output devices present in the environment is another topic high on our agenda. The document-centric approach described in the Software Infrastructure section provides a basic mechanism for matching device capabilities with the application preference and the state of the user. More importantly, it allows the application developer to specify interactions in a higher-level, device-independent manner, thus reducing the cost of development and maintenance. We are looking into how to support multi-modal, multi-device interactions (e.g. an animated avatar with a speech interface) using this approach.

During the design of BlueSpace we made many decisions that need to be validate and improved by short and long term user studies. For instance, it is hard to quantify whether the context-aware notification system is disruptive or not. Also, our working status model requires long term studies to evaluate how real people actually use the system, the social codes that emerge from their interaction, and whether it, in fact, decreases "drive-by interruptions" and increases productivity. Our main tool for those user studies is BlueSpace itself, since we have available an easily reconfigurable platform where users can be put in direct contact with a real computerized environment.

On a longer-term horizon, we would like to explore the relationship between mobile computing and smart environments. Mobile devices have increasingly become an integral part of the workspace computing. How to provide infrastructure services to mobile devices

while preserving the integrity of the private, virtual space remains a challenging issue. We plan to extend the BlueSpace components with service discovery, security, and gateway services, and to incorporate applications to facilitate remote collaboration and telepresence. We believe the infrastructure-centric approach that we have taken allows us to leverage a large body of on-going work in these areas.

Acknowledgements

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