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The Context Toolkit: Aiding the Development of Context-Enabled Applications

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ABSTRACT
Context-enabled applications are just emerging and promise richer interaction by taking environmental context into account. However, they are difficult to build due to their distributed nature and the use of unconventional sensors. The concepts of toolkits and widget libraries in graphical user interfaces has been tremendously successful, allowing programmers to leverage off existing building blocks to build interactive systems more easily. We introduce the concept of context widgets that mediate between the environment and the application in the same way graphical widgets mediate between the user and the application. We illustrate the concept of context widgets with the beginnings of a widget library we have developed for sensing presence, identity and activity of people and things. We assess the success of our approach with two example context-enabled applications we have built and an existing application to which we have added context-sensing capabilities.

Keywords
Context-enabled or context-aware computing, ubiquitous computing, toolkits, widgets, applications development

INTRODUCTION
Over the last decade, several researchers have built applications that take advantage of environmental information, also called context, to enhance the interaction with the user. The construction of these context-enabled applications is cumbersome, and currently no tools are available to facilitate the development of this class of applications. This paper presents a toolkit for developing reusable solutions for handling context information in interactive applications.

We first define the notion of context, and through a brief review of the literature identify the key challenges of developing applications that sense context, followed by an overview of the paper.

What Is Context?
Environmental information or context covers information that is part of an application's operating environment and that can be sensed by the application. This typically includes the location, identity, activity and state of people, groups and objects. Context may also be related to places or the computing environment. Places such as buildings and rooms can be fitted with sensors that provide measurements of physical variables such as temperature or lighting. Finally, an application may sense its software and hardware environment to detect, for example, the capabilities of nearby resources.

Sensing context information makes several kinds of context-enabled applications possible: Applications may display context information, capture it for later access and provide context-based retrieval of stored information. Of major interest are context-aware applications, which sense context information and modify their behavior accordingly without explicit user intervention.

Why Use Context?
Usage scenarios of typical context-enabled applications found in the literature have led us to identify recurrent challenges, which we further detail below.

Mobile tour guides are designed to familiarize a visitor with a new area. They sense the user's location and provide information relevant to both the user and the location she's at [1, 3, 6, 10]. Likewise, office awareness systems sense users' locations, but are also interested in their activities to help people locate each other, maintain awareness or forward phone calls [12, 17, 18]. In ubiquitous computing systems, devices sense and take advantage of nearby resources: a handheld computer located next to an electronic whiteboard may make use of the larger display surface or allow the user to interact with other nearby handheld users [14, 18]. Finally, context-based retrieval applications gather and store context information and allow later information retrieval based on context information. For instance the user can ask a note-taking application to pull up the notes taken at a previous meeting with the group she's meeting with currently [9, 13].

Why Is Using Context Difficult?
The above usage scenarios raise the following difficulties, which are common to most applications that use context

information. These difficulties stem from the very nature of context information:

1) It is acquired from unconventional sensors. Mobile devices for instance may acquire location information from outdoor GPS receivers or indoor positioning systems. Tracking the location of people or detecting their presence may require Active Badge devices, floor-embedded presence sensors or video image processing.
2) It must be abstracted to make sense for the application. GPS receivers for instance provide geographical coordinates. But tour guide applications would make better use of higher-level information such as street or building names. Similarly, Active Badges provide IDs, which must be abstracted into user names and locations.
3) It may be acquired from multiple distributed and heterogeneous sources. Tracking the location of users in an office requires gathering information from multiple sensors throughout the office. Furthermore, context sensing technologies such as video image processing may introduce uncertainty: they usually provide a ranked list of candidate results. Detecting the presence of people in a room reliably may require combining the results of several techniques such as image processing, audio processing, floor-embedded pressure sensors, etc.
4) It is dynamic. Changes in the environment must be detected in real time and applications must adapt to constant changes. For instance, when a user equipped with a handheld moves away from the electronic whiteboard, the user loses the benefit of the wide display surface and the application must modify its behavior accordingly. Also, context information history is valuable, as shown by context-based retrieval applications. A dynamic and historical model allows applications to fully exploit the richness of context information.

Although these problems are recurrent we lack conceptual models and tools to describe solutions to these problems.

Overview Of Paper

This paper presents a context toolkit aimed at developing reusable solutions to address these problems and thus make it easier to build context-enabled applications. The inspiration for this context toolkit is the success of toolkits in graphical user interface (GUI) development. The context toolkit builds upon the widget concept from GUI toolkits. In the same way GUI toolkits insulate the application from interaction details handled by widgets, the context toolkit insulates the application from context sensing mechanics through widgets. We first introduce the concepts underlying the context toolkit and describe applications it allowed us to build. We discuss details of the toolkit implementation that address specific problems of distribution, heterogeneity and dynamism that are not addressed by GUI toolkits. We conclude with future plans for the evolution of the context toolkit.

DESIGNING A CONTEXT TOOLKIT

The context toolkit we have developed relies on the concept of context widgets. Just as GUI widgets mediate between the application and the user, context widgets mediate between the application and its operating environment. We analyze the benefits of GUI widgets, introduce the concept of context widget, detail its benefits, and explain how context-enabled applications are built using these widgets.

Learning From Graphical User Interface Widgets

It is now taken for granted that GUI application designers and programmers can reuse existing interaction solutions embodied in GUI toolkits and widget libraries. GUI widgets (sometimes called interactors) span a large range of interaction solutions: selecting a file; triggering an action; choosing options; or even direct manipulation of graphical objects [11].

GUI toolkits have three main benefits:

- They *hide specifics* of physical interaction devices from the applications programmer so that those devices can change with minimal impact on applications. Whether the user points and clicks with a mouse or fingers and taps on a touchpad or uses keyboard shortcuts doesn't require any changes to the application.
- They *manage the details* of the interaction to provide applications with relevant results of user actions. Widget-specific dialogue is handled by the widget itself, and the application often only needs to implement a single callback to be notified of the result of an interaction sequence.
- They *provide reusable building blocks* of presentation to be defined once and reused, combined, and/or tailored for use in many applications. Widgets provide encapsulation of appearance and behavior. The programmer doesn't need to know the inner workings of a widget to use it.

Although toolkits and widgets are known to have limitations such as being too low-level or lacking flexibility, they provide stepping stones for designing and building user interfaces and developing tools such as User Interface Management Systems (UIMS). With context widgets, we aim at providing similar stepping stones for designing and building context-enabled applications.

What Is A Context Widget?

A context widget is a software component that provides applications with access to context information from their operating environment. In the same way GUI widgets insulate applications from some presentation concerns, context widgets insulate applications from context acquisition concerns.

Context widgets provide the following benefits:

- They *hide the complexity* of the actual sensors used from the application. Whether the presence of people is sensed using Active Badges, floor sensors, video

image processing or a combination of these should not impact the application.

- They *abstract context information* to suit the expected needs of applications. A widget that tracks the location of a user within a building or a city notifies the application only when the user moves from one room to another, or from one street corner to another, and doesn't report less significant moves to the application. Widgets provide abstracted information that we expect applications to need the most frequently.
- They *provide reusable and customizable building blocks* of context sensing. A widget that tracks the location of a user can be used by a variety of applications, from tour guides to office awareness systems. Furthermore, context widgets can be tailored and combined in ways similar to GUI widgets. For example, a *Presence* widget senses the presence of people in a room. A *Meeting* widget may rely on a *Presence* widget and assume a meeting is beginning when two or more people are present.

These benefits address issues 1 and 2 listed in the introduction. From the application's perspective, context widgets encapsulate context information and provide methods to access it in a way very similar to a GUI toolkit. However, due to the characteristics of context and notably issues 3 and 4 mentioned in the introduction, distribution and dynamicity, the context toolkit has some unique features. We briefly describe the similarities with GUI toolkits and point out some major differences.

How Applications Use Context Widgets

Context widgets have a state and a behavior. The widget state is a set of attributes that can be queried by applications. For example, an *IdentityPresence* widget has attributes for its location, the last time a presence was detected, and the identity of the last user detected. Applications can also register to be notified of context changes detected by the widget. The widget triggers callbacks to the application when changes in the environment are detected. The *IdentityPresence* widget for instance, provides callbacks to notify the application when a new person arrives, or when a person leaves.

Context widgets are basic building blocks that manage sensing of a particular piece of context. We expect full-fledged context-aware applications to take advantage of multiple types of context information and rely on a rich dynamic model of their operating environment. To this end, our widget toolkit provides means of composing widgets. For example, a widget designed to detect the kind of activity people in a classroom are engaged in could combine the information provided by presence widgets and activity sensing widgets using, for instance, audio and video analysis. Based on information provided by widgets such as the number of people in the room, their location in the room, the speakers, activity in the front of the classroom, the composite widget would detect activities such as lecture, group study, exam, etc.

So far, context widgets are very similar to GUI widgets, however there are important differences:

- Context widgets live in a distributed architecture because context may need to be acquired from multiple distributed sources. Widgets rely on three kinds of distributed components: generators that acquire context information, interpreters that abstract it and servers that aggregate information. Applications, widgets and the components they rely upon may be distributed. This feature of the toolkit addresses issue 3 listed in the introduction
- Context widgets monitor environmental information that may be needed at any time by an application. Thus a context widget is active all the time, and its activation is not, as with GUI widgets, driven by applications. This feature, along with other characteristics of the toolkit described in the implementation section, addresses issue 4.

The context toolkit aims at enabling easier development of context-enabled applications. To assess our objective, we have built context widgets we expect applications to need frequently and have developed applications based on these widgets.

BUILDING CONTEXT WIDGETS

In this section, we describe two of the context widgets that we have built. These context widgets aim at surveying an indoor environment. We show examples of their use in the applications described in the next section. The first widget, *IdentityPresence*, is attached to a specified location and senses the surrounding environment for the presence of people and their identity. The second widget, *Activity*, continuously monitors the surrounding environment for significant changes in activity level.

The *IdentityPresence* Widget

The *IdentityPresence* widget is placed in a pre-specified location and reports the arrival and departure of people at that location. The identities of the people arriving and departing as well as the times at which the events occurred are also made available to applications. The information this widget provides is useful for any location-aware application like tour guide or applications that track people.

The *IdentityPresence* widget provides applications with the attributes and callbacks listed in Table 1.

Widget Class	IdentityPresence
Attributes	
Location	*Location the widget is monitoring*
Identity	*ID of the last user sensed*
Timestamp	*Time of the last arrival*
Callbacks	
PersonArrives (location, identity, timestamp)	*Triggered when a user arrives*
PersonLeaves (location, identity, timestamp)	*Triggered when a user leaves*

Table 1. Definition of the *IdentityPresence* widget.

All widgets acquire context information through generators. *Generators* are components that encapsulate a

single sensor or a set of closely related sensors and the software that acquires raw information from the sensor(s).

The *IdentityPresence* widget could be implemented using any number of generators, including voice recognition, Active Badges, video/image recognition, keyboard and login information, or even a combination of these. The generator that is chosen affects neither the definition of the widget nor any application that uses the widget. The attributes and callbacks provided by the widget are independent from the actual implementation, thus sheltering the application from the specifics of the sensors used. Our current implementation of the *IdentityPresence* widget uses Dallas Semiconductor's iButtons [4], passive tags with unique identifiers and storage and computing capabilities or alternatively passive TIRIS RF tags [15].

The *Activity* Widget

The *Activity* widget senses the current activity level at a location such as a room. It may be used to sense the presence of people if they are active in a room. While it can not provide reliable presence information by itself, it provides additional environmental information and can, for example, sense that people are actively discussing in the room. The widget is instantiated at a pre-specified location. Applications that use the *Activity* widget specify parameters for receiving callbacks, as seen in the table below.

The attributes and callbacks supported by the *Activity* widget are listed in table 2.

Widget Class	Activity
Attributes	
Location	*Location the widget is monitoring*
Timestamp	*Time of the last change in activity level*
AverageLevel	*Activity level (none, some, a lot) averaged over a user-specified time interval*
Callbacks	
ActivityChange (location, AverageLevel, timestamp)	*Triggered when the activity level changes from one level to another*

Table 2. Attributes and callbacks of the *Activity* widget.

The *Activity* widget has been implemented with a microphone, but like the *IdentityPresence* widget, it could be implemented with any appropriate generator, such as an infrared sensor, video image analysis, or a combination of these.

Other Context Widgets

We have also constructed other widgets as part of the context toolkit. The *NamePresence* widget is similar to the *IdentityPresence* widget. Instead of providing an artificial user ID for a user whose presence has been detected, this widget provides the user's actual name. The *PhoneUse* widget provides information about whether a phone is being used and the length of use. The *MachineUse* widget provides information about when a user logs onto or off of a computer, his identity, and length of her computing session. The *GroupURLPresence* widget provides a URL relevant to the research group a user belongs to when her presence is detected. An application describing its use is given in the following section. The completeness and overall structure of the entire context widget library is an interesting open research issue.

BUILDING APPLICATIONS WITH THE CONTEXT TOOLKIT

In this section, we describe three applications we have built to assess the actual benefits of our context toolkit. To reiterate, the expected advantages of the toolkit are to hide complexity, provide appropriate interpretation of context information and ease overall construction through reusable widgets.

In/Out Board

Motivation

The first application we have built is the electronic equivalent of a simple in/out board that is commonly found in offices. The board is used to indicate which members of the office are currently in the building and which are not (see figure 1). In both the academic and corporate world, we often find ourselves trying to determine whether someone is in the office in order to interact with her.

Figure 1. Screenshot of the in/out board application. The dot next to a user name is green if the user is in and red if she is out.

Context Information

The in/out board application is an example of a context-viewing application. It gathers information about the participants who enter and leave the building and displays the information to interested users. The context information is a participant's identity and the time at which they arrived or departed. This application is interested in events when people pass the single entry point into the building. Therefore, only a single instance of the *IdentityPresence* widget is required, and is located at the entrance to the building. Through the use of this widget, the context-sensing infrastructure is successful in hiding the details of how the context is sensed from the application developer.

Future Extensions

With the use of additional *IdentityPresence* widgets located in strategic areas (e.g., offices, meeting spaces) within the building, the in/out board application can easily be extended to a person tracking application. It would display the location of users throughout the building on a map. By

adding an *IdentityPresence* widget to sense the identity of the user watching the display, we would be able to tailor the display to show only information relevant for this user, such as close colleagues or members of the same research group.

Information Display

Motivation

For our second application, we built an information display, similar to those found in the literature [7, 19]. We aim to show that the context toolkit can be used to reimplement existing context-enabled applications. This application displays information relevant to the user's location and identity on a display adjacent to the user. It activates itself as someone approaches it, and the information it displays changes to match the user, her research group, and location.

Context Information

The context information used by the information display is the location of the display, the identity of the user, the research group the user belongs to and information that is interesting to that research group. A single *GroupURLPresence* widget is used to supply the information to this application. The widget installed nearest to the display is used. When a user's presence is detected by the widget, it makes a URL about the user's research group available to the interested application. The application shows the contents of the URL on the nearby display.

This application does not deal with the details of how the context information is sensed, meaning the widget is successful at hiding the complexity of the sensing infrastructure. As well, the widget provides the appropriate information and detail to the application. For example, this application could have been implemented with an *IdentityPresence* widget. This would have required the application to determine what research group the nearby user was in and find information relevant to that research group. However, using the *GroupURLPresence* widget alleviated the need to perform these extra steps.

Future Extensions

The information display application provides the beginnings of a simple tour guide application, where the user is mobile and displays are static. Essentially, a basic context-aware tour guide [1, 6] displays information relevant to the location and the identity of the person viewing the information. The information display is a very simple example of a tour guide with only one location of interest, but with additional displays and information providing widgets, it could be extended to build a full tour guide application.

DUMMBO Meeting Board

Motivation

For our third application, we chose to augment an already existing system, the DUMMBO (Dynamic Ubiquitous Mobile Meeting Board) project at Georgia Tech [2]. DUMMBO is an instrumented digitizing whiteboard that supports the capture and access of informal and spontaneous meetings. Captured meetings consist of the ink written to and erased from the whiteboard as well as the recorded audio discussion. After the meeting, a participant can access the captured notes and audio by indicating the time and date of the meeting.

In the initial version of DUMMBO, recording of a meeting was initiated by writing or erasing activity on the physical whiteboard. In the revised, context-aware version of DUMMBO, we wanted to have recording triggered when a group of two or more people gathered around the whiteboard. We also wanted to use information about when people were present around the whiteboard and their identities to help in visualizing and accessing captured material.

Context Information

This application belongs to the context-aware class of applications. It uses context to modify its own behavior (e.g., automatically starting the recording when enough people are standing around the whiteboard). The context information used is the participants' identities, the time when they arrived at or left the mobile whiteboard, and the location of the mobile whiteboard. The application uses multiple *NamePresence* widgets, one for each location where DUMMBO could be moved to in our research lab, and one on DUMMBO itself to detect the presence of users. Once again, the application could have used *IdentityPresence* widgets but the *NamePresence* widgets provided the appropriate level of detail, requiring fewer steps on the part of the programmer and application.

Adding Context to DUMMBO

This application was augmented on both the capture side and the access side. On the capture side, information about how many people were close to the whiteboard is used to determine when to start the audio and notes recording. During the access phase, participants can use context information such as the location, time and date of the meeting, and the names of participants at the meeting to retrieve the recorded meeting information. This extra context makes it easier for participants to retrieve the meeting information at a later date.

Again, the details of the widget are kept transparent from the programmer. The programmer, another member of our research group, simply needed to determine which widgets he was interested in and handle the information those widgets were providing. In all, the application only required changing/adding 25 lines of Java code (out of a total of 892 lines) and modifications were localized in a single class file. The significant modifications include 2 lines added to use the context toolkit and widget, 1 line modified to enable the class to handle callbacks, and 17 lines that are application specific. Comparatively, the size of the context toolkit is about 12400 lines of Java code.

To achieve such easy retrofitting of context handling capabilities in existing applications, the context toolkit manages the mechanics of context acquisition and abstraction. We now turn to the relevant implementation details of these mechanics.

CONTEXT TOOLKIT IMPLEMENTATION DETAILS

We have previously outlined the application programmer's interface to the context toolkit by describing what is a context widget, giving some examples of widgets and demonstrating context-enabled applications that make use of the widgets. There are some important requirements (points 3 and 4 in the introduction) for the context toolkit having to do with its distribution, composition, heterogeneity and dynamism that we will address in this section.

Distribution

The context infrastructure must accommodate distribution of applications, widgets and the components they rely upon, across a network. Applications may require the services of several widgets distributed across different machines, as described in the DUMMBO application.

In addition, widgets themselves may be distributed. A widget may consist of any number of three types of components: generators, interpreters, and servers (see figure 2). A generator, as described earlier, acquires raw context information from hardware or software sensors and provides it to widgets.

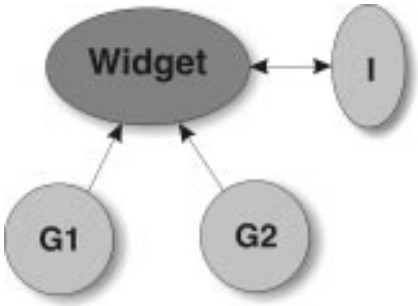

Figure 2. A context widget and supporting components. Arrows represent the data flow. In this example, the widget gets raw context data from two generators G1 and G2 and requests the services of an interpreter I.

An interpreter abstracts raw or low-level context information into higher level information. An example of this was seen in the DUMMBO application where the basic *NamePresence* widget used a generator to obtain a user ID for the user whose presence was detected. An interpreter is used to abstract the raw ID information into an actual user name. Interpreters can be used for more than simply converting between types of data. They play an important role in widget composition.

Composition

Context widgets can be composed to provide richer context information while reusing existing widgets. For example, composing the *IdentityPresence* and *Activity* widgets could provide a simple *Meeting* widget. By combining the information about the presence of people at a location and an estimate of their activity, one can roughly detect if the people are engaged in a meeting or if they are just sitting in the same place and no collaborative activity is taking place. The *Meeting* widget would gather information from the *IdentityPresence* and *Activity* widgets assigned to the room. It would rely on an interpreter to analyze the information provided by both widgets and deduce if a meeting is taking place. The interpreter could assume a meeting is taking place if the number of people in the room is at least two and the activity level is "a lot". The *Meeting* widget would provide this information to applications through two callbacks: *MeetingStarts* and *MeetingEnds.*

When dealing with generators that provide uncertain information such as video image analysis techniques, interpreters are used to assess the validity of the information provided. They perform either simple filtering (such as rejecting any result whose confidence factor is less than a given threshold) or comparison and consolidation of the results from multiple uncertain generators.

Taking composition one step further, a server is a special kind of widget that collects, stores and interprets information from other widgets. To pursue the GUI widget analogy, it is similar to a container widget like a frame or a dialog box: it maintains a high-level model of related components. Servers are typically used to model context information of real world entities such as users or places. By acting as a gateway between applications and elementary widgets, servers hide even more complexity within the context infrastructure. For example, in the PersonFinder (extended in/out board) application, rather than have the application subscribe to every *IdentityPresence* widget in the building, it simply subscribes to the building server and receives the same desired information.

As well, to address the privacy concerns that are raised by context-sensing, a server can be used to encapsulate a privacy manager for its given domain (whether it is a person, place, or thing). For example, if applications access their desired context information via servers, then users who don't want particular information made public can modify the privacy restrictions for their personal server to keep that information from anyone but themselves or a trusted group.

Communicating Across Heterogeneous Components

To allow easy communication between the components that make up a widget and between widgets and applications, we needed to support a single, simple communications and language model. To allow as many systems as possible to employ our context toolkit, we only assume that the underlying system supports TCP/IP.

To further this goal of platform independence, our communication model uses the fairly ubiquitous HTTP protocol and our language model uses the ASCII-based Extensible Markup Language (XML) [16]. ASCII text is the lowest common denominator available on a wide variety of platforms for data transfer and XML allows us to describe structured data using text. Implementations of HTTP servers and clients libraries that can interpret XML are beginning to appear and have minimal resource requirements, allowing communication across a wide variety of platforms and devices.

Handling Dynamism

Context information is inherently dynamic. As changes in the environment are detected, applications must be given

the opportunity to easily adapt to these changes. This requires two components: providing access to the information using a standard mechanism and allowing access to only the desired information. Furthermore, context information history has value for applications as well as widgets and must be preserved.

The communications model just described aids in allowing applications access to the changing information. To ease programmatic access to context information, we provide a standard subscription mechanism, enabling an application to be notified of context changes, and a polling mechanism, enabling an application to inquire about context information.

Context widgets allow applications to specify conditions that must be fulfilled before they will be notified of a change in the context. This shifts the task of filtering unwanted information to the context infrastructure and away from the application. An example of this can be seen in the DUMMBO application. This application needs to know where the mobile whiteboard is at all times, so it must subscribe to all *NamePresence* widgets in the building. However, it is only interested in callbacks where presence of the mobile whiteboard is detected. By specifying this condition in the subscription, the application can more efficiently deal with the information that it is particularly interested in and not have to deal with all the presence detections for other objects and people.

For our context toolkit to be able to support context-based retrieval applications, all context widgets store historical data in a database. Applications or interpreters can retrieve past data from a widget. Aside from context-based retrieval, we expect this feature to be useful for building interpreters that rely on patterns of behavior deduced from machine learning techniques.

RELATED WORK

Previous research efforts have proposed infrastructures for context-enabled applications. We review them in this section and point out the differences with the context toolkit.

Schilit's infrastructure for ubiquitous computing is probably the earliest attempt at providing services for handling context [14]. In this work, context information is primarily location. Location is acquired from an Active Badges infrastructure. Active Map objects gather context information related to a physical spatial area and make it available to client applications. This approach assumes that a location can be assigned to all context information.

The stick-e framework addresses the needs of context-aware notes used, for example, to make up a tour guide [3]. Notes use SGML tags to register interest in context information and set conditions on context values that will trigger the display or execution of the note. Although this model is potentially wide ranging, it is mainly aimed at displaying context information or triggering simple actions. The mandatory use of notes as clients of context information makes it difficult to retrofit an existing application with context sensing or even build an application that modifies its behavior in response to a changing environment.

The Situated Computing Service (SitComp) has objectives very close to ours: it seeks to insulate applications from sensors used to acquire context [8]. A SitComp service is a single server that encapsulates context acquisition and abstraction and provides both an event-driven and a query interface to applications. The sensors used are location-tracking tags very similar to Active Badges. Our work goes one step further by advocating a modular structure made of several widgets dedicated to handling specific pieces of context information and laying the grounds for reusable context handling building blocks.

Although simply aimed at conveying context information to other users in a CSCW setting, the AROMA prototype shares an interesting feature with our context toolkit [12]. It provides "abstractor" objects that abstract high-level context information from the raw information captured by sensors.

Finally, CyberDesk was inspirational to the work presented in this paper [5]. Although it only deals with one piece of context information, namely the user's current text selection, it proposes a modular structure that separates context acquisition, context abstraction mechanisms and actual client services.

FUTURE WORK

The context toolkit we have presented still needs additional work to accommodate the wide range of context-enabled applications. Areas we want to explore are extending the toolkit capabilities, structuring the widgets design space, and heuristic rules for designing with context widgets.

To extend the toolkit capabilities, we need to address the issue of resource discovery and temporal composition. Resource discovery enables applications to adapt transparently to changes in the infrastructure. Widgets, generators, or interpreters may become active or inactive, migrate from machine to machine and even modify the set of capabilities they provide. Resource discovery will allow us to better handle the dynamism requirement. In the current version of our toolkit, context widgets can be composed to provide richer information. However, we don't provide means to impose temporal constraints within the composition mechanism. In a setting where context information changes rapidly, combination of information from different widgets may need to occur in a guaranteed time frame.

Work on the context widget library we have described in this paper is only in its initial stage. Although it has proved useful in its current state, the number and variety of widgets should be increased to effectively support a wide range of context-enabled applications. An immediate concern is to devise a structure for organizing widget classes in the library. Identifying the basic pieces of context information needed by applications, defining widgets to handle them and then combining these widgets will allow us to enhance the widget library and construct more diverse applications. So far, Presence, Identity, and Activity appear

to be core types of context information and we plan to build upon this list.

CONCLUSION

We have presented a toolkit that supports the development of context-enabled applications. The context toolkit was inspired by the success of GUI toolkits and has similar benefits: building blocks called context widgets provide reusable solutions for context handling; by delegating details of context handling to the toolkit, we achieve separation of concerns between context sensing and application semantics.

To assess the validity of our toolkit-based approach, we have developed a small number of context widgets and example applications described in this paper. We were able to build new context-enabled applications, replicate canonical context-enabled applications found in the literature and retrofit an existing application with context capabilities.

More information on the work described in this paper is available on the web at http://www.cc.gatech.edu/fce/contexttoolkit/. The context toolkit software is available from the same web page.

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