

An Infrastructured-Architectural Model (IAM) for Pervasive & Ubiquitous Computing

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Abstract. An extensible and modular architecture called *IAM* that addresses this information-routing problem while leveraging significant existing work on composable Internet services and adaptation for heterogeneous devices is described here. *IAM*'s central abstraction is the concept of a *trigger*, a self-describing chunk of information bundled with the spatial and/or temporal constraints that define the context in which the information should be delivered. The *IAM* architecture manages triggers at a centralized infrastructure server and arranges for the triggers to be distributed to pervasive computing devices that can detect when the trigger conditions have been satisfied and alert the user accordingly. The main contribution of the architecture is an infrastructure-centric approach to the trigger management problem. We argue that pervasive computing devices benefit from extensive support in the form of infrastructure computing services in at least two ways. First, infrastructure adaptation services can help manage communication among heterogeneous devices. Second, access to public infrastructure services such as MapQuest and Yahoo can augment the functionality of trigger management because they naturally support the time and location dependent tasks typical of pervasive-computing users. We describe our experience with a functional prototype implementation that exploits GPS to simulate an AutoPC.

1 Introduction

The Internet-connected ScreenFridge [11] the Microwave Bank [4] and the new AutoPC [6] appear to be primitive first steps in the direction of pervasive computing. If these efforts sound a bit outlandish, there's a good reason: the devices are solutions in search of a problem. Yet the devices do have something in common with Web browsers, pagers, cell phones, grocery lists, and to-do notes stuck on the door. We are inundated with information of all kinds, arriving over various media, and targeted for various tasks do this tomorrow, check up on that when you're in the office, call me back, and so on. This suggests that one natural target for pervasive computing is *data management*-getting information into the temporal or spatial *context* in which it will

be most useful, and using pervasive computing devices to accept or deliver it. It has been argued [12] that pervasive computing will have succeeded when computers-“disappear into the infrastructure” and we find ourselves using computer-assisted task-specific devices, as opposed to computing devices *per se*. In particular, we describe a simple pervasive computing architecture to address the above problem, along with an implemented prototype using off-the-shelf PC's and pervasive computing devices.

We take an infrastructure-centric point of view: like PDA's and handheld devices, pervasive computing devices will be fundamentally dependent on infrastructure “glue” in order to be truly useful. For PDA's, the original rationale behind this assertion was the need for adaptation: since a primary application of the devices is information retrieval from the Internet, infrastructure support is needed to adapt these devices to a network infrastructure not designed for them [7]. The analogous argument for pervasive computing is that humans receive and deal with information in a variety of temporal and spatial contexts, and although pervasive computing devices are useful as “end-unit” sensors and actuators to assist with information management tasks, infrastructure support is needed to tie them together and address the distributed information management problem.

1.1 A real-time situation

Considering the following scenario: Opening your refrigerator to take out a drink, you notice that there is only one can left. You scan its UPC with the scanner attached to your refrigerator. This action adds drink to your shopping list. You plan to have guests over this weekend, and make a note on your ScreenFridge that you need to replenish your supply of drinks by Friday. The next day, on your drive home from work, you happen to approach a local supermarket. Your GPS-enabled AutoPC, previously informed by your refrigerator that purchases need to be made, signals that you are near a grocery store, and if it is convenient, that you should stop by the supermarket on the way home. Suppose you do not act on the opportunity, and Friday rolls around and you still have not visited the supermarket; in this case, a message to buy drinks is sent to your pager, or an alarm is triggered in your PDA, or both. The key observation that follows from the above example is that information is rarely useful at the time and place it is generated. Rather, the information must be re-presented later, where and when it can be acted on. That is, information is most useful when it is delivered in the correct temporal or spatial context.

1.2 Ideal Infrastructure

This simple example illustrates two important ways in which pervasive computing relies on infrastructure support. The first, and obvious, dependence is for communication: items are added to the “shopping list” by your refrigerator but the list itself needs to be accessible elsewhere. The information has to be transported between devices. The less obvious but more important dependence is on *infrastructure services*. By these we refer to publicly-accessible interactive services that perform on-demand computation over large datasets. In the context of the present work, an

infrastructure service is simply one that does not run on any of the pervasive computing devices themselves it may run in the public Internet or in a private home-area network. Infrastructure Services may be necessary for any of several reasons:

Data rapidly changing: Timely information, such as traffic reports, news, and stock quotes, changes too rapidly to make continuous distribution practical for intermittently connected users. Furthermore, devices such as PDA's and the AutoPC may not have constant connectivity; therefore, such services require infrastructure support.

Unwieldy datasets: One example of an unwieldy dataset is a UPC database. In the example given in the previous section, the refrigerator may need to translate the UPC to a product name so that the shopping list is readable by humans. Although the refrigerator might cache the UPC's of frequently-purchased products, a general UPC translation service would necessarily be infrastructural.

Computation: The computation required to generate a result may exceed the storage or CPU resources available to a small device. For example, some online mapping services such as MapQuest support queries of the form "Given a starting location, find the geographically closest businesses of a given type."

Examples of Web-based infrastructure services that have the above properties include mapping and driving directions services, zip code lookup, search engines and business directories, upto-the-minute financial information, and online auctions. Several aspects of our motivating example assume the ability to leverage such services: translating UPC's to product names, locating a supermarket through a directory service such as Yahoo!, converting the address to GPS coordinates ("geocoding") through programmatic interfaces to mapping services such as MapQuest, and possibly sending a text-based, on-demand notification to a pager or similar device through an Internet gateway, such as Airtel. Recognizing the need for infrastructural support for pervasive computing devices, we present IAM, a uniform architecture for addressing the information management and infrastructure dependence issues exposed by the example given in the previous section. In the following sections, we describe the IAM architecture, discuss our prototype implementation in progress, and show how this approach promises rapid deployment by leveraging other existing research, both in design philosophy and implementation.

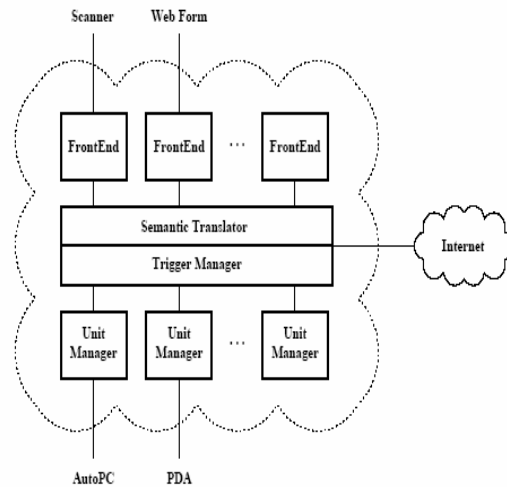


Fig. 1. Overall IAM Architecture

2 IAM Architecture

2.1 Triggers

The notion of a trigger is central to IAM. We use the term *trigger* to mean information paired with its useful context. Conceptually, a trigger is some action that should be taken when a previously stated condition is satisfied. The trigger is not novel to IAM; it has been in use in the database community for years. However, IAM extends the classical database notion of a trigger by allowing decentralized evaluation of triggers. Triggers are pushed to end devices, such as DA's or AutoPC's, allowing evaluation to occur at those devices. Although in some cases evaluation could occur at a central location such as a server, in other cases the end device is the only appropriate device to evaluate the trigger, because information such as location may be local to the device and not known by others. IAM provides the ability to (a) determine which devices should receive which triggers, (b) route the selected triggers to the devices, and (c) possibly assist in determining when to fire them. The IAM architecture is shown in Figure 1. The system is well-connected to the Internet infrastructure and consists of several components. *FrontEnds* are used for input into a *Semantic Translator*, which in turn interfaces with a *Trigger Manager*. Also, a *Unit Manager* exists for each type of end-device and the function of each component is described.

2.2 Managing Triggers

Conceptually, a trigger is composed of a condition and an action. When the condition evaluates to true, some action should occur. Typically, the desired goal is the

completion of some high-level task. The high level task is translated by the system's Semantic Translator to a corresponding set of triggers. Some tasks may be represented as a single trigger, such as an alarm for a specific time. Others may be represented as a combination of several triggers. In the supermarket example, the high-level task can be mapped to two distinct triggers: 1) A trigger that is fired when a certain spatial constraint is satisfied, or 2) a trigger that is fired when a certain temporal context is met. A *term* is a primitive that evaluates to true when a particular spatial or temporal constraint is satisfied. All triggers are stored in the IAM system; a subset is forwarded to those devices that can evaluate the trigger's condition.

2.3 Example illustrated

Coming back to the example the chain of events in relation to the proposed architecture:

I. A user scans the UPC of a bottle, and enters a requirement to buy drinks by Friday. The scanner sends this information to the IAM FrontEnd designed for the scanner's interface. In general, for every input format, there is a FrontEnd that collects information about high-level tasks.

II. The FrontEnd then forwards the information to the Semantic Translator which translates high-level tasks into sets of triggers. Since IAM is well-connected to the Internet, it can retrieve pertinent information such as the location and hours of local supermarkets using a publicly-accessible service such as Yahoo or MapQuest. Using this information, the translator produces two triggers from the high-level task "Buy drinks by Friday":

Trigger 1:

- Condition: $(\text{location} \in R) \wedge (t > T1) \wedge (t < T2)$

- Data: "Since you are driving home from work and passing by a grocery store at location R , you could stop to buy drinks for Friday."

Trigger 2:

- Condition: $(t = T)$

- Data: "Buy drinks today."

Note that the condition in Trigger 1 is composed of three terms: $(\text{location} \in R)$, $(t > T1)$, $(t < T2)$. The time terms represent the period of time associated with the user's drive home from work. In general, a condition can be composed of an arbitrary number of terms, connected by logical operators.

III. IAM then inspects its list of accessible end-devices; each of the end-devices and its corresponding properties were made known to IAM, by previous registration. Hence IAM is aware of information such as processing power and connectivity of each end-device, and is capable of distributing triggers to end-devices. The first trigger above is be routed to an AutoPC equipped with GPS, and the second trigger routed to a PDA.

IV. Each end-device stores the trigger(s) assigned to it, and when the appropriate context is satisfied, renders the data to the user. For example, when the AutoPC nears a supermarket during open hours, the user is informed of the event, perhaps by the

AutoPC's text-to-speech facility. Because IAM knows each device's capabilities, it can ensure that each device only receives data that it can suitably render.

V. When the event is acted on, the user will indicate that the high-level task has been accomplished to the AutoPC, which will in turn inform IAM. Because the AutoPC is weakly connected, it can notify IAM via email that the task has been acted on. IAM can then proceed to cancel other triggers that were created from the same high-level task, as they are now unnecessary. The next time other devices communicate with IAM, extraneous triggers will be deleted from those devices as well.

3 Model Implementation

3.1 Overview

Triggers are the mechanism by which reminders are produced in a context where the information is useful. A trigger object contains trigger data, condition, and an optional special handler, which replaces the default handler if special actions are to be taken. The user directly enters trigger information into the IAM System, which determines which devices are capable of processing specific triggers and distributes the triggers accordingly. We use the term *Mobile Information Appliance* (MIA) to refer generically to a device that can act as the endpoint of a trigger.

IAM comprises the following components:

The Frontend provides an interface through which the user can enter trigger information-conditions to be met for the trigger to go off and the actions that need to be taken when the trigger goes off. Although the prototype supports only Web form entry of trigger conditions directly (eliminating the need for a Semantic Translator), keeping the frontend separate from the Trigger Manager allows incremental addition of more sophisticated input mechanisms, e.g. a simulated ScreenFridge.

The Trigger Manager runs in the infrastructure and stores all the triggers entered by the user. This component must be up and accessible all the time. This forwards the triggers to the appropriate end-points upon request using the various unit managers.

The Unit Manager is an MIA specific component residing in the infrastructure. It hides the peculiarities of each type of MIA from the Trigger Manager and helps in transferring triggers from the Trigger Manager to the MIA's.

The Trigger Acceptor resides on the MIA and communicates with the appropriate unit manager in the infrastructure to download triggers if and when necessary.

The Trigger Handler resides on the MIA and is responsible for evaluating the trigger condition and executing the appropriate handler. The Trigger Handler consists of three elements. *Term Evaluators* interface with the device clock or GPS receiver to evaluate the temporal and spatial terms in the condition; when a term changes in value, a callback is sent to the Condition Evaluator. The Condition Evaluator re-evaluates the Boolean expression of terms each time a callback from the Term Evaluator is received; when the expression evaluates to true, the Data Handler is invoked to renders the trigger's data to the user using whatever notification mechanism is appropriate to the MIA (window popup, text-to-speech conversion, alarm sound, etc.)

3.2 Details of Implementation

We have leveraged several existing “off the shelf” software tools and technologies for putting together the system: Ninja [8], TeleType software [13] (for GPS), and Microsoft Windows CE. We are using a GPS enabled Philips Nino (running WinCE), which we expect to replace with an AutoPC in actual use. In the current implementation, the MIA (Nino) communicates with the Unit Manager using the standard Windows CE serial cradle. The Trigger Acceptor, a piece of native WinCE code that runs on the Nino, initiates a connection to the Unit Manager, a Ninja ISPACE service running in the infrastructure. Triggers are transferred between the Trigger Acceptor and the Unit Manager using a simple TCP-based serialization protocol. In a real implementation, we expect to use a two-way wireless connection rather than the cradle and allow for the possibility of proactively pushing triggers to an MIA capable of asynchronous receiving (rather than waiting for an explicit request from the MIA). The Unit Manager gets the triggers from the Trigger Manager, another Ninja ISPACE service that maintains a database of trigger objects in an XML-like serialized form. The Trigger Handler on the WinCE device converts from the internal representation of the trigger to a C++ trigger object. The term evaluators in the Trigger Handler access the GPS data and register for time-based notifications via the WinCE API. Although primitive, the prototype demonstrates the feasibility of the IAM system. We implemented the motivating example scenario using this prototype: the user enters a trigger through the frontend asking the system to remind him if he is near the supermarket in a specified time interval, and when the GPS coordinates indicate that the user is close to the supermarket and the current time is within the specified limits, a window pops up on the Nino.

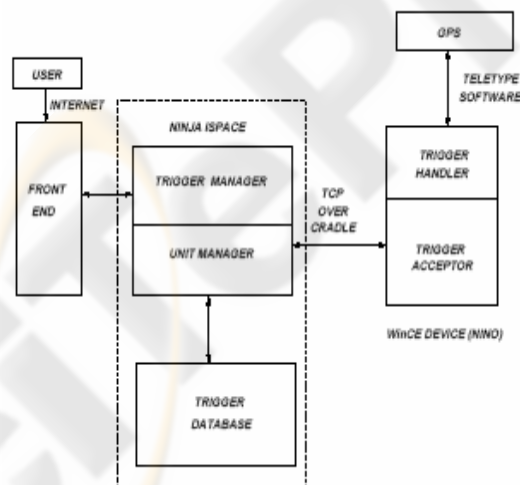


Fig. 2. IAM system

The high degree of modularity of the prototype should allow us to improve it by incrementally adding more sophisticated user input mechanisms and incorporating new devices.

4 Related Works

4.1 Pervasive Computing

In *The Design of Everyday Things* [14], Donald Norman advocates moving information “into the world” as a sound design technique for everyday objects. Pervasive computing using the IAM architecture is a concrete instantiation of this principle: at the moment a useful piece of information is created, it can be routed to an information management system whose responsibility is to ultimately deliver it into the physical context in which it will be useful. In Weiser and Want’s seminal Tab system, the wearable devices called Tabs relied on extensive infrastructure support to provide functionality such as tracking a user around a building, automatically opening doors for her, forwarding her calls to the phone nearest her current location, and having a terminal retrieve her preferences when she sits down to use it. We believe the intimate connection between truly pervasive computing and strong infrastructure support, as demonstrated in the Tab system, is fundamental” hence our strategy of combining a flexible and robust framework for “programming the infrastructure”, i.e. Ninja, with a novel data-management architecture whose central whose central abstraction is the context-sensitive trigger and whose primary responsibility is the creation, management, and routing of triggers, with infrastructure support. Steve Mann’s head-mounted augmented reality system [9] allows a computer-generated image to be super-posed with the “real” image that is seen through the glasses. Among other things, the overlaid image can be used to annotate the virtual counterparts of real-life objects; for example, a virtual “buy drink” sign hung on the supermarket can be seen as the user passes by the supermarket while wearing the glasses. By treating the glasses as a device capable of instantiating a location-based trigger, IAM provides a unified framework for supporting such reality augmentation devices.

IAM can enhance the “smartness” of smart spaces by coupling automatic actuation with the correct context; for example, your alarm clock might go off half an hour earlier than usual, based on its knowledge of a meeting you have scheduled and the report of an accident on your route to work.

4.2 Infrastructure Computing

The UC Berkeley TACC [5] framework enables the creation of interactive Internet applications by composing modules that either implement new functionality or leverage the functionality of another already-deployed remote service. For example, an early TACC application was a “meta-search” engine that queried various existing search engines and ranked the collated results; this application could be composed with a thin-client browser adaptor [10] to deliver an efficient multi-engine search service to a handheld PDA device with a limited user interface. In this sense, TACC was a primitive attempt to provide a framework for *programming* the Internet using existing services as building blocks. The Java-based Ninja [8] framework improves on TACC by providing strongly-typed composable programmatic interfaces for service modules and providing a core set of services and primitives for building and

composing modules. We used Ninja as a starting point for building IAM. The need for interoperability among diverse devices and heterogeneous networks has been extensively addressed via work on transformational and other adaptation proxies TACC demonstrated the value of putting transformation services into the infrastructure; since the IAM Trigger Manager already acts as a centralized resource in our pervasive computing architecture, it is a natural place to collocate transformation capability.

4.3 Triggers

Triggers have been in use in the relational database community since at least SQL version 3 [14]. In that context, a trigger is a specification of some actions to take whenever a modification to a database table results in some constraint on the relation being met. We have extended the basic trigger in two ways. First, recognizing that dynamic attributes such as location and time are fundamental to our task of moving information to the right context, we have provided the ability to instantiate triggers based on these attributes. We rely on the specific abilities of pervasive-computing devices to accomplish this. Second, we allow partial and distributed evaluation of triggers. Specifically, we look for affinities between terms in the trigger condition and the specific abilities of each device.

5 Issues addressed

5.1 Handling multiple users

Most information transmitted to and from pervasive devices is likely to be private by default. However, we believe many users will prefer to avoid the complexity of operating a Home Base in their home, delegating this instead to an Internet data center or comparable infrastructure installation. Note that many people already use public infrastructure for email and gatewaying messages to pagers, so the idea of using public infrastructure for private data is not without precedent. We intend to build IAM as a shared infrastructure for private data, but leave open the possibility to extend the system to support group-accessible triggers.

5.2 Trigger Consistency and User Interface

In the initial prototype, triggers are entered using a Web-form interface. If IAM is to be widely accepted, other interfaces must be designed to make it easy for users enter trigger information. As the motivating example suggests, one possible interface is the UPC scanner on the ScreenFridge; this interface is an easy way to enter "shopping-list" reminders, but it is clearly limited to the particular context. Therefore, architecture is designed so that any number of such interfaces modules, or Frontends, can easily be added.

5.3 Semantic translation

When easier-to-use interfaces are integrated into the system, there must be a mechanism to translate high-level "requests" such as scanning an item on a UPC scanner into a set of primitive triggers. In many cases, a user-preferences file will aid the translation; such a file could include locations of interest (e.g., grocery stores within a certain radius of a user's home), the user's default schedule, and a link to the user's actual schedule. In keeping with the composable applications philosophy, we are making this translation mechanism separable from and composable with the Trigger Manager to allow maximum flexibility for future work in this area.

5.4 Multiterm conditions

Since certain condition parameters, such as those that depend on rapidly-changing information, are best evaluated in the infrastructure, there may exist conditions where some terms should be on the device and some terms should be evaluated at the IAM trigger manager. As was the case with trigger consistency, this problem is complicated by the fact that some devices are only intermittently connected.

6 Conclusions

The architecture described in the previous sections brings coherence to a number of other problems whose relationships to each other were previously not obvious. It provides a framework that naturally accommodates such diverse devices as the AutoPC, the ScreenFridge, and augmented reality glasses.

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