Smart Kindergarten: Sensor-based Wireless Networks for Smart Developmental Problem-solving Environments

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ABSTRACT

Despite enormous progress in networking and computing technologies, their application has remained restricted to conventional person-to-person and person-to-computer communication. However, continual reduction in cost and form factor is now making it possible to imbed networking - even wireless networking - and computing capabilities not just in our PCs and laptops but also other objects. Further, a marriage of these ever tinier and cheaper processors and wireless network interfaces with emerging micro-sensors based on MEMS technology is allowing cheap sensing, processing, and communication capabilities to be unobtrusively embedded in familiar physical objects. The result is an emerging paradigm shift where the primary role of information technology would be to enhance or assist in "person to physical world" communication via familiar physical objects with embedded (a) micro-sensors to react to external stimuli, and (b) wireless networking and computing engines for tetherless communication with compute servers and other networked embedded objects. In this paper we present the application of sensor-based wireless networks to a "Smart Kindergarten" that we are developing to target developmental problem-solving environments for early childhood education. This is a natural application as young children learn by exploring and interacting with objects such as toys in their environment. Our envisioned system would enhance the education process by providing a childhood learning environment that is individualized to each child, adapts to the context, coordinates activities of multiple children, and allows continual unobtrusive evaluation of the learning process by the teacher. This would be done by wirelessly-networked, sensor-enhanced toys and other classroom objects with back-end middleware services and database techniques. We explore wireless networking, middleware, and data management technologies for realizing this application, and describe challenges arising from ad hoc distributed structure, unreliable sensing, large scale/density, and novel sensor data types that are characteristic of such deeply instrumented environments with inter-networked physical objects.

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1. INTRODUCTION

The focus and application of wireless information technology so far has largely been on using low power, portable computers, enhanced with multimedia I/O peripherals, for richer "person to computer" and "person to person" interactions. However, the interaction of users with computers and peripherals is quite different from their interaction with objects in physical environments. This requires that users and their applications adapt to information technology, rather than the other way round, thereby limiting the application of information technology in many cases (e.g. children, people with disabilities). However, the relentless march of microelectronics technology is coming to the rescue in the form of (a) cheaper and tinier processors and memories, (b) cheaper and tinier communication systems, and (c) cheaper and tinier MEMS sensors and actuators. Indeed, in a not too distant future, a single chip would integrate processor, memory, radio, and sensors, all in a die of few square millimeters, costing a few dollars, and consuming a few milliwatts (e.g. SmartDust project at Berkeley [1]). Such technology would allow processing, communication, sensing, and perhaps even actuation capabilities to be unobtrusively embedded in familiar physical objects that the users interact within their environments, and lead to systems where these familiar physical objects are tetherless peripherals with capabilities of reacting to external stimuli, and wirelessly communicating with each other and with background servers. In the not too distant future, such technology will bring interaction and intelligence to commonplace inanimate objects in our environment.

The emerging ability of computing infrastructures to sense and act on the physical environment suggests a future where the primary role of wireless technology would become one of enhancing "person to physical world" interaction, rather than the conventional "person to computer" and "person to person" communication. Smart environments instrumented with sensor-and-wireless-enhanced objects would be able to sense events and conditions about people and objects in the environment, and act upon the sensed information or use it as context when responding to queries and commands.

An interesting application of such deeply instrumented physical environments with inter-networked physical objects that we are exploring is a Smart Kindergarten. Children learn by exploring and interacting with objects such as toys in their environments, and the experience of having the environment respond (causally) to their actions is one key aspect of their development. We would use the ability to sense and act on the physical environment to create and evaluate smart developmental problem-solving environments in pre-school and kindergarten classroom settings. A wireless network of toys, composed of toys with embedded modules that provide processing, wireless communication, and sensing capability, would be used as the application platform together with a background computing and data management infrastructure. For example, a networked toy may provide aural, visual, motion, tactile and other feedback, and be able to sense speech, physical manipulation, and absolute and relative location. Our eventual system would enhance the education process by providing a childhood learning environment that is individualized to each child, adapts to the context, coordinates activities of multiple children, and allows unobtrusive evaluation of the learning process by the teacher.

This paper presents some of the challenges in wireless networking, middleware services, and data management that are essential for realizing a scalable infrastructure for the above vision of a Smart kindergarten, and in general for deeply instrumented physical environments with wirelessly inter-networked embedded systems. These environments require a transition from a focus on conventional general purpose computing and communication to a focus on embedded computing and interaction with the physical world brings in problems such as ad hoc distributed structure, large scale and density, unreliability, and physical stimulus and reaction. Architectures, algorithms, and formalisms that have been developed for networking, computing, and information management in conventional information processing are grossly mismatched to these physical, embedded, and reactive systems. Existing research [2] is focused on sensors, radios, and infrastructures to support them. Issues of data management, middleware services, and network architecture, although critical, are currently afterthoughts at best. The paper also briefly describes our ideas in solving some of these problems in the context of a project that is in its early stages but where we are working with an elementary school (UCLA's Corinne A. Seeds University Elementary School) to actually create and deploy our envisioned Smart Kindergarten system, and with experts in education (UCLA's National Center for Research on Evaluation, Standards, and Student Testing) providing the application domain expertise.

2. RELATED RESEARCH

At a broad level the research challenges presented by the Smart Kindergarten application are related to research in the area that is variously referred to as Ubiquitous Computing, Smart Spaces, or Pervasive Computing. Perhaps the original vision for such research could be traced to Mark Weiser's seminal article in Scientific American [3] where he advocated using a large number of invisible networked computing systems (i.e. computers hidden everywhere in the woodwork) to "activate" the world. Weiser envisioned "a physical world that is richly and invisibly interwoven with sensors, actuators, displays, and computational elements, richly and invisibly interwoven embedded seamlessly in the everyday objects of our lives and connected through a continuous network". Over the past few years several projects have explored the paradigm of Ubiquitous Computing in various forms. Perhaps the most relevant to Smart Kindergarten system, because of its focus on education, is the Classroom 2000 project at Georgia Tech [4] where an instrumented classroom was designed to capture the traditional university lecture experience. The technical focus was on automatically capturing a rich, multimedia experience and providing useful access into the record of the experience by automatically integrating the various streams of captured information. Electronic notes taken by the students and the teachers are captured as pen strokes linked to lecture notes projected on a LiveBoard (a huge vertical pen computer in the form of a whiteboard) for the teacher and displayed on pen tablets for the students, and augmented with audio and vide recordings to produce time-stamped media-enhanced records of lectures.

The challenges presented by the Smart Kindergarten system differ in several dimensions. First, our focus is not the traditional synchronous lecture but the seemingly unstructured asynchronous playing and problem-solving oriented environment in the classrooms for young kids. The asynchronous and problem-solving nature has two implication: it is much harder to make sense out of the captured information, and it is essential for the environment to not only capture but to also appropriately react in real-time in a context-sensitive fashion to further the problem-solving process. Second, the user base of young kids is much more challenging than university students. For example, the level of computing environment obtrusiveness that young kids can tolerate is much less than that tolerated by older students who may adapt to user interface restrictions. Third, we seek to exploit new technology advances to embed sensing, computing, and wireless communication capabilities in all sorts of objects in the classroom environment, such as toys, so as to make available a much richer source of sensory information about the environment than mere traditional audio, video, and pen strokes. For example, awe envision tracking spatial position and orientation. We need to address problems of scale and density (large number of objects in a space will be instrumented); diversity of data types with a large dynamic range of rate, latency, and processing requirements; and, noisy, redundant sensing sources.

Also relevant to Smart Kindergarten is the observation that recent trends in computing have focused on embedding technology in everyday objects to make them more intelligent, such as sensor-equipped toys that interact with children. For example, MIT Media Lab's Toys of Tomorrow (TOT) program has been instrumental in the creation of many such toys. Toys such as stuffed dolls and building blocks, which kids use to play and learn, are increasingly becoming robotic computers with sophisticated microchips embedded in their bodies. One example is Crickets-tiny devices that can be programmed, contain sensors, and can communicate via infrared technology with other Crickets [5]. Crickets have been embedded into balls and beads to be used as digital manipulatives in students' science explorations. Another example from TOT is Storytelling [6] where stories stored on the computer are linked to particular stuffed animals. Children's interactions with different stuffed animals trigger different stories from the computer. However, the keys challenges in our vision of Smart Kindergarten are not in how to create new toys or other objects with embedded sensing, computing, and wireless communications. Rather, the key challenges are in (i) creating new networked sensing approaches, (ii) networking protocols optimized for large scale and high density, and (iii) processing and analysis of data generated by all these sensors to extract useful information and patterns after appropriate aggregation, filtering and reduction.

3. SYSTEM ARCHITECTURE

The Smart Kindergarten system that we are designing will consist of a large number of sensors wirelessly connected to a background infrastructure that provides storage and computing services. While some of the sensors might be dumb, in general the sensors would also have associated processing capability to allow functions such as signal processing for feature extraction to be performed locally, which might be preferred to sending raw data over the wireless network. The infrastructure is "in the walls" and virtually unrestricted in its capability; the bottlenecks are in the power, computation, storage, and communication capabilities of the embedded devices. For hardware we are implementing a miniature "sensing + wireless communication + embedded processing" module that will be embedded in the objects in the real-life Kindergarten that we will soon instrument. The module is based around Ericsson's Bluetooth module mated to a custom board that we are designing with sensor I/O.

3.1 Sensing Infrastructure

A crucial component of our system is the sensor instrumentation infrastructure. Our goal is to capture sensor data such as identity, absolute location, relative location, audio/speech, image/video, orientation, motion, acceleration, touch/pressure, light, and temperature at appropriate spatial granularity, and feeding the extracted information after appropriate processing to a behind-the-scene data management server. In addition to sensors, we also envision feedback in the form of audio, light, and even animated toys. A key requirement is that all this instrumentation be physically unobtrusive, which means that in most instances the hardware should be miniature and wireless. However current technology restrictions on size, energy efficiency, wireless data rate per Hz-m3, and spectrum availability clearly limit the density with which one can instrument the space. Our approach is to separate the three broad categories of instrumentation: cameras for video/image (high bit rate), microphones (and speakers) for audio/speech (medium bit rate), and other sensors (which are mostly low bit rate). We envision wall mounted steerable cameras; embedded wireless microphones and speakers at strategic places, objects in the environment, and perhaps microphones on kids for localized speech and audio capture and feedback; and, embedded sensors for touch, pressure, and acceleration in toys and classroom objects to detect their manipulation by the kids.

One of the most important sensor requirements in our application is the need to accurately locate (3D position, orientation) and identify objects and users (kids, teachers). We are interested in both absolute location to track where a user or object is, and relative location to identify spatial configurations composed of multiple users and objects. We would like to be able to know both absolute location information such as that a kid is in the corner, as well as relative location information such as that kid A is near a toy or near kid B. Techniques for fine-grained estimation and tracking of location and orientation of a large number of objects is therefore a key challenge.

Another key requirement is low-power video/image capture, and automatic coordinated detection and capture of "interesting' events. The key research challenge here are techniques whereby the cameras can be autonomously triggered and focused based on events from other sensors such as audio or motion.

The multiple, localized, directional microphones and speakers, coupled with location and id sensors, can also enable some useful application level mechanisms. First, multiple microphones help simplify the speech recognition problem in multiple speaker scenario. Second, acoustic multilateration based on signal strengths can be used as an additional sensory mechanism to localize the position of the speaker. Third, concurrent data from other sensors assist in the speech recognition process. The identity and location of users provided by other sensors could be used to identify the speaker, and select the corresponding acoustic models. Further, the dictionary could be adapted based on information about the speaker's location and the objects in the speaker's immediate surrounding. For example nouns corresponding to the names of nearby objects and persons, and verbs corresponding to possible actions related to those objects can be dynamically added to the dictionary associated with a speaker. Such context-adaptation can somewhat simplify the otherwise challenging task of recognizing children's speech.

3.2 Wireless Networking and Sensor Middleware Services

Another set of challenges arise from the needed wireless networking and middleware services for the sensor infrastructure described above. We envisage our instrumented room-sized physical environments to have O(100) to O(1000) objects with embedded sensing, computing, and wireless communication capabilities. As mentioned in the previous section, data rates vary from around O(10) bits per second for sensors such as touch sensors to > O(100,000) bits per second for streaming video. Putting a radio or other communication capability into the objects provides physical connectivity; however, to make them useful in a larger context a networking and middleware services infrastructure is required. From a networking perspective, this is a particularly challenging environment in terms of the density, diversity of rates and quality of service needs, severe size and power constraint on the sensor modules embedded in common objects, and very high aggregate bandwidth (~ 100 Mbps). Wired networking is clearly out because of size and unobtrusiveness constraints, leaving some form of wireless networking as the option. We envision a two-tier wireless network architecture within the physical room, as shown in Figure 1. At the lower tier would be small overlapping networks (piconets, to borrow Bluetooth's jargon) of devices communicating using short range, low power, and low cost radios such as Bluetooth or RF Monolithic's low power radio TR1000 transceiver. We anticipate that a few 10s of such short-range networks will exist at any given time within the room, and a device or user may roam from one to another. At the upper tier we will have one (or more than one if higher aggregate bandwidth is desired) high-speed longer-range wireless LAN, such as one based on commonly available 2.4 GHz, 11 Mbps IEEE 802.11b wireless LAN radios. The wireless LAN will connect the lower tier piconets and selected high-speed sensors to the wired network infrastructure via wireless LAN access point. The lower tier networks will connect to the wireless LAN via custom bridges that we will design, and densely embed in the environment. A device will talk to the nearest inter-tier bridge. In essence, our architecture is a pico-cellular architecture with the inter-tier bridges acting as basestations, and the

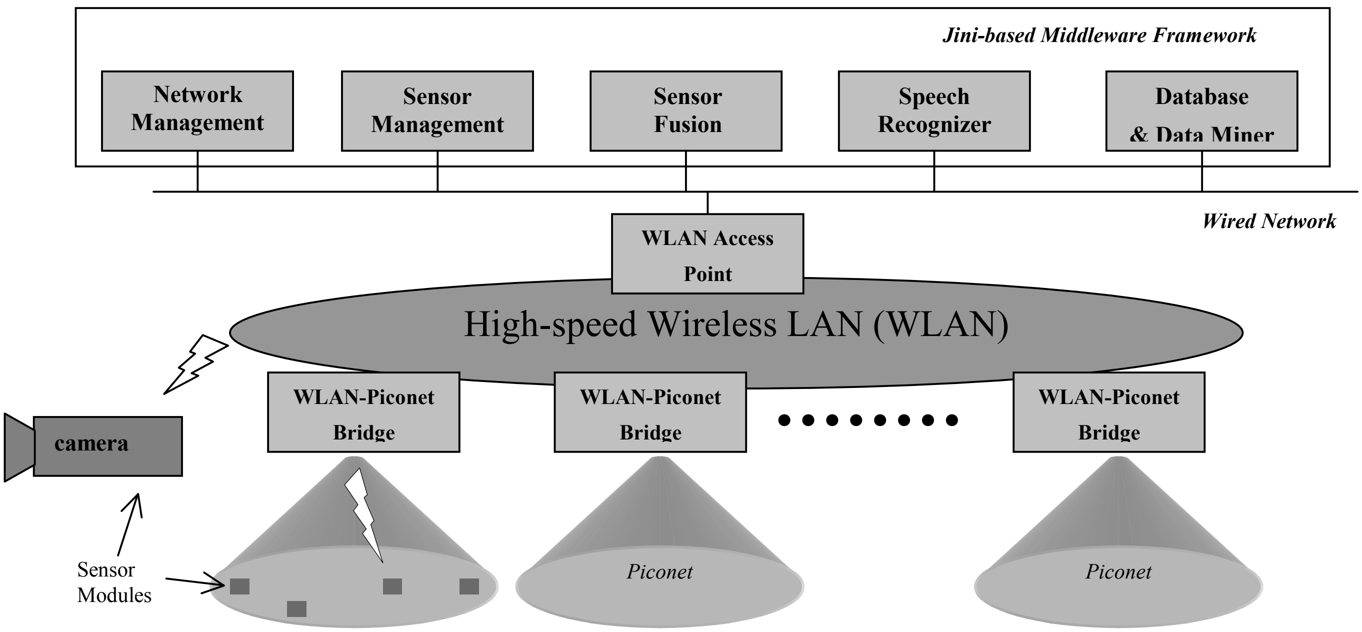

Figure 1: Proposed Network and Service Architecture

basestations themselves being interconnected wirelessly. It is conceivable that a device may still not find an inter-tier bridge to which it can talk directly, in which case we will rely on multihop routing in an ad-hoc augmented pico-cellular fashion. Traditional wireless access protocols, optimized for a small number of relatively similar devices in pure ad hoc or pure cellular networks, are mismatched for the large number of wirelessly networked embedded devices in a small volume, with a large diversity of rates and quality of service requirements, and an ad hoc augmented cellular architecture. Research challenges include energy efficient medium access and channel allocation algorithms for an operating environment where there are 10s of devices per square meter, some low rate and some high rate, and some with streaming requirements while other with low latency constraints.

Inherent to our vision is that the above network is shared by multiple users and easily accessible to application developers. A key challenge is the architecture of a middleware layer that would provide a set of distributed services and an API to the networked embedded objects for application writers. Services would provide support for (a) special communication patterns such as spatial addressing required by sensor-oriented applications, (b) allocation, admission control, and scheduling of network resources to specific tasks, (c) media-specific processing such as a shared speech recognition service, (d) battery power-aware operation, and (e) tracking context information, and generating and distributing events based on context changes. As an example, a "call Mary" command spoken by the user might result in a nearby microphone sending the waveform to a shared speech recognition service, whose output will then go to a context-aware command interpreter service that will make use of the context information provided by a context-tracking service, and finally a set of network resources and services (e.g. a speaker and a microphone at the same location, and a telephony server) will be allocated and scheduled by the middleware taking into account quality of service (QoS) and sharing constraints. In a different scenario, the speech recognition output might go to the sensor data management system, described in the next section, for capture, data mining, and profiling. We envision using a distributed service framework to provide basic mechanisms for realizing our middleware services. The sensor middleware will provide services for sensor data fusion and cooperative sensor processing, whereby the events and information captured by multiple sensors of the same type or by different types of sensors may be combined to develop a single more reliable reading. For example, location information may be obtained from multiple cues, and combined to get a more accurate estimate.

3.3 Sensor Data Management Service

Reaping the full capabilities of the instrumented Smart Kindergarten environment requires a proper addressing of data management issues. Crucial is the ability to modify behavior of an application based on knowledge of its context of use, and the ability to capture live experiences for recall and analysis. Proper off-line and on-line management of sensor data is the key. The research on conventional data and information management is not directly applicable to tasks such as querying in a sensor instrumented physical environment where the resolution to a query may require a context dependent fusion of information available from a large number of unreliable, time varying, and mobile sensors. The specific data management challenges are:

- Data models, query languages and storage structures to support capture, query, mining, and browsing repositories of audio, video, and a variety of sensor data.

- Design and development of a sensor data management service, which supports data fusion from a set of sensors that are not known a priori. This service must provide means for available sensors to declare their capabilities, and for "information services" to be dynamically formed from currently available sensor data. Such a software structure may be built on formalisms such as Bayesian Belief Networks, and built upon the more basic services provided by the wireless networking infrastructure and middleware services.
- Applications that are users of the data management services may exploit the available sensor data over a range of different time scales. Consider our target domain, the Smart Kindergarten. Over a short time scale, an adaptive learning application might be interested in real-time interpretation of sensor data and events about a child's actions and dynamic context so that the stimuli generated by the system can be suitably tailored. Over a longer time scale, an application to monitor a child's progress might want to mine the sensor data off-line for patterns and to develop a profile to characterize an individual child and his/her developmental history. This may be used to evaluate progress as well as to personalize and optimize subsequent interactions with that child. Algorithms for on-line real-time sensor data interpretation, as well as off-line sensor data mining are therefore an important challenge.
- A particularly important data management task is the mining of profiles from sensor data to characterize individuals so that the environment can be personalized and optimized for the individual.

The instrumented classroom can potentially provide a great deal of useful data. Our ultimate goal is to determine how this data can be used in educational assessment to good advantage. The actual capture of the data is a first step. We are creating a software

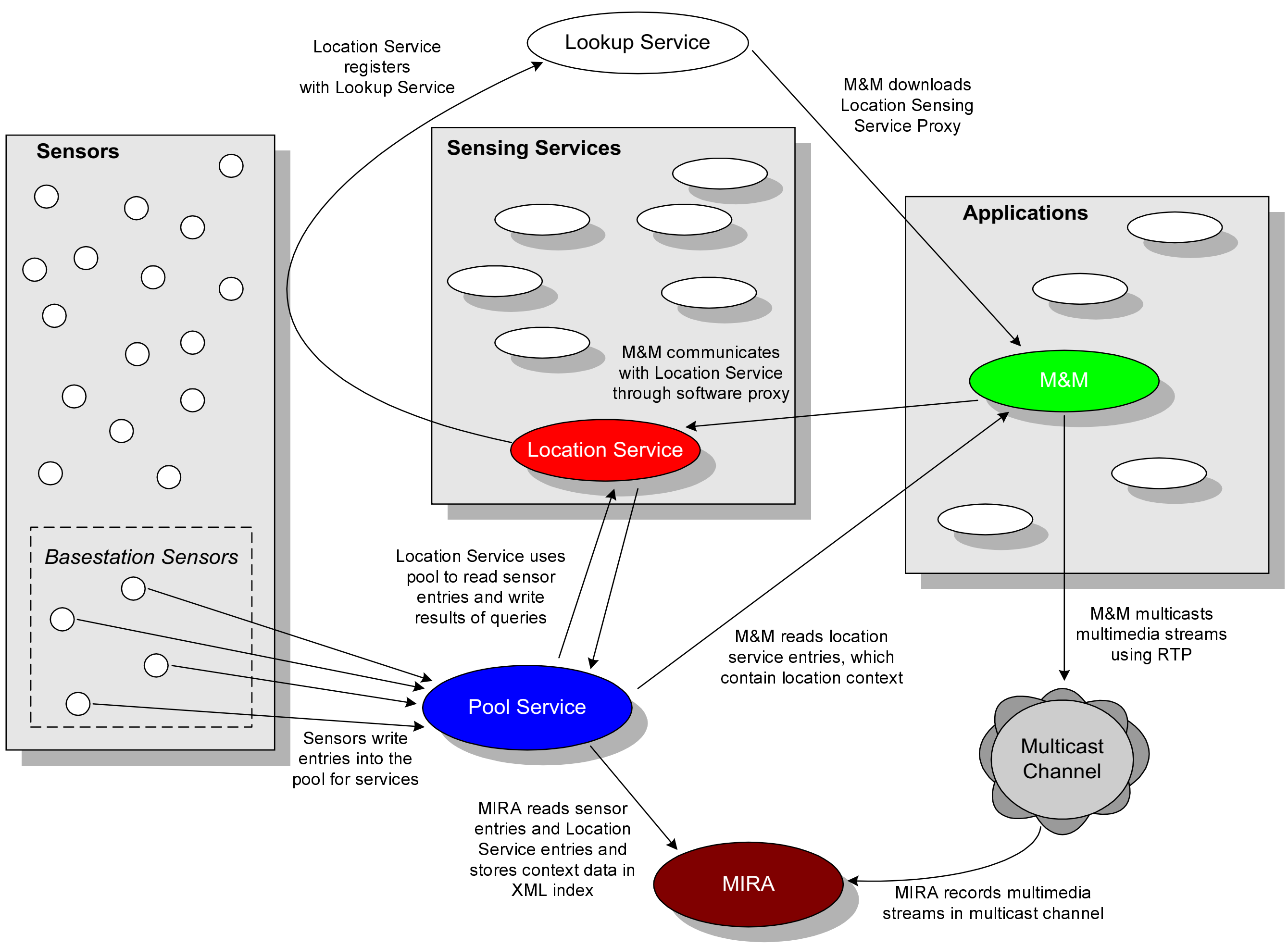

Figure 2: Software Infrastructure

infrastructure as shown in Figure 2 to provide the following services:

- We expect the available sensors to change both slowly (as for example we introduce additional sensors, or sensors fail) or more frequently (e.g., when people leave the room carrying a sensor on them). Using software such as Jini, available sensors to be registered as services providing physical level data.
- Software services implementing Bayesian networks can also be registered which provide the means of probabilistically inferring semantically higher-level events based on the raw sensor data.
- Other services, e.g., for real-time audio stream speech to text processing, can also be registered.
- Audio and video are stored in a repository as separate objects requiring real time delivery. All other data (sensor data, word tags obtained from speech to text software, etc.) is stored as XML documents and can be flexibly indexed, queried, and browsed.
- We refer to the preceding items as "context information" for the activities being recorded. A capability for augmenting this record offline is also needed, e.g., for more costly video analysis or by human interpretation and annotation.

It is important to note that the physical sensor data, as well as the derived or inferred data, can be recorded under control of the experimenter. This provides flexibility in several ways.

- Real-time derivation of context data provides the basis for considering a real-time reactive environment, e.g, where a toy can react in real-time to a child.
- Off line augmentation of the recording via processing that is not possible in real-time.
- Rederivation of semantics on recorded episodes based on alternative or improved algorithms for interpretation; either the belief network based inferencing or improved audio/video-processing algorithms. Since a major challenge in this project is to better understand how to use the data that technology is making available in education, the ability to go back and reinterpret previously collected recordings is essential.
- Data mining applied at various levels of abstraction. The amount of data as well as its complexity will stress available algorithms. One method of adaptation may be to apply algorithms at a higher level of abstraction where data is expected to be less voluminous.
- The software may be adapted to many sensor rich environments and specific applications by providing the appropriate Bayesian Networks for inferring events that are semantically meaningful in that application and which take as base information the available sensor data. The functional software, e.g., which interprets the audio streams, will also have to be adapted, e.g., to deal with children's voices. This system provides an immediately available facility for the teachers and researchers on this project to start collection of data.

Finally, a key component of the data management service would be a automated user profiling system. The role of this system will be to help users navigate through the instrumented physical environment, enable applications to reason about the environment, and facilitate planning and execution of actions within the environment. There are numerous potential application scenarios, even when restricted to our target application domain of the Smart Kindergarten. For example, the user profiling system can enable parents and teachers to better monitor the problem solving progress of children by reducing the raw sensor data into profiles. One can also use it to identify, both on an individual and group-wide aggregate basis, the popular parts of the Smart Kindergarten environment and the objects that attract the highest attention. This data could be used to organize the physical environment and populate it with objects which are either popular or which have been used by children who have made the most rapid progress in their education and/or social skills on the hypothesis that there may be a causal link between the objects and the developmental progress. The data could also be use to reconstruct the context leading to classroom episodes identified as interesting by the teacher (e.g. proximity of two kids leading to a fight, or a kid spending too much time in isolation), and establish sensor data pattern triggers to automatically detect such episodes, both on-line and off-line.

4. APPLICATION VIEW

In the prototype system, objects that children play with on a regular basis will be wirelessly networked and have sensing capabilities. A wireless multimedia data network, with protocols suitable for handling a high density of wireless objects, interconnects the toys to each other and to database and compute servers via toy network middleware and API. Sensors embedded in toys and worn by children as badges will allow the database servers to discover and keep track of context information about the kids and the toys, and also enable aural, visual, motion, tactile and other feedback. Compute and storage servers will provide media-specific services such as speech recognition, in addition to managing the resources in the distributed system.

We are targeting early childhood education as a testbed for our technologies for two reasons. First, the classroom environment provides a test site where the technology can be stressed. Children interacting with each other and with sensor-equipped objects provide a dynamic and noisy environment, which we expect will evolve in surprising and unexpected ways. Thus, one measure of success is the extent to which the technology for deeply-instrumented physical environments can seamlessly adapt to such changes. The second reason to focus on an educational context is that we expect that our proposed multi-tiered approach-the coordinated use of sensors, communications, context awareness, and behavioral profiling-will provide the capability to comprehensively investigate student learning processes on a scale and at a level of detail never before attempted. Our ideas reflects research toward a system architecture that will be general enough to support the gathering and interpretation of student telemetry: the systematic measurement of meaningful behavior over time with respect to the activities children are engaged in, when they are doing them, and the local and global contexts in which they are working. The data collected will be based on measures of what we believe represent effective problem-solving strategies in young children. From an assessment perspective, it is the integration of these capabilities that offers the potential to develop new student assessments and advance our understanding of student learning. These technologies make feasible the collection of meaningful student process and performance data that are unobtrusive, accessible, and reliable. From an instructional perspective, we can use the student assessment information to provide feedback to the teacher about individual progress on learning indicators that track performance over time.

Our initial system will be based on instrumenting play objects with 2-way wireless networking capabilities and embedded location, proximity, and speech I/O. These toys, in the form of objects familiar to children, will allow the environment to be instrumented with I/O devices in disguise. While simple to implement, this initial system will nevertheless enable applications that require unobtrusive capture of a child's actions (e.g. capturing what a child says when she is reading aloud). The long-term vision is a system that adaptively triggers educational tasks based on spatial and temporal context triggers (e.g., same group of kids together again, two kids doing the same thing nearby) and records kids actions and responses for evaluation. Later, as our embedded wireless communication and sensing infrastructure and technology matures, we will explore more sophisticated application scenarios within environments composed of multiple elements, using sensor technology to detect specific object configurations created by the child, and associating the achievement of those configurations to specific actions such as rewards or further tasks.

5. CONCLUSIONS

From a technology perspective the key challenges outlined in this paper are on networking, middleware, and data management techniques for physical environments with embedded networked objects with sensing and communication capabilities. Specific challenges resulting from our system are network protocols for large-scale dense wireless networks of embedded devices, new approaches to naming and addressing, user location tracking, interpretation and fusion of heterogeneous sensor data, and user profile discovery in networked physical environments. However, the contributions will go beyond mere networking and computing techniques, and will also have a significant impact on how wireless information technology can be integrated into early childhood education and assessment. Information technology in early childhood education has so far largely meant putting a PC in the classroom with software packages that allow stimulus-responses modes limited to the capabilities of a multimedia computer. During the last several years there has been rapid development of electronic toys that purport to interact with children (e.g., Furby, electronic books). In reality, these interactions are simple stimulus-responses modes based largely on the present interaction with the child and with limited memory of the interaction. The deeply instrumented physical environment with wirelessly inter-networked embedded systems that we envision allow educational applications to integrate student-level assessment as a formal component of the application, thus leading eventually to the idea of individualized student feedback on an ongoing basis to promote the development of math skills.

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