NIST Information Technology Laboratory Pervasive Computing Initiative

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1. Overview

The next great computing paradigm shift, to pervasive computing, is already well under way and will have no less of an impact on industry, government, and daily life than the personal computing revolution. ***Pervasive computing*** refers to the emerging trend toward numerous, easily accessible computing devices connected to each other and to an increasingly ubiquitous network infrastructure. This trend will likely create new opportunities and challenges for Information Technology (IT) companies to place computers and sensors in virtually every device, appliance, and piece of equipment in buildings, homes, workplaces, factories, and even clothing. Within five years vendors will offer portable and embedded devices containing low-cost systems-on-a-chip (SOC) with enough CPU, memory, and input/output logic to execute complex software applications, and use pico-cellular wireless communications. Effective pervasive computing must present user interfaces distributed across numerous, often small, and even invisible devices. This requires new techniques in measurement, software testing, management of the frequency space, and human-computer interactions. Failure to develop and exploit these pervasive computing technologies and techniques may be very costly to U.S. IT companies.

The field of pervasive computing is in its infancy and many of the technologies required to make it a reality are immature and high risk. ITL has launched a pervasive computing initiative to investigate the technical and standards roadblocks impeding integration of the emerging and existing technologies. Consistent with ITL's strategic plan, the initiative involves working with industry to develop and demonstrate test methods, reference data, tests, proof of concept implementations, and standards to help pull the underlying technologies forward and thus help the field mature and grow. The initiative is multi-disciplinary and takes advantage of the expertise of several Divisions within ITL and creates new expertise. Areas addressed by the initiative include: information access and user interfaces, networking, software, and security. The pervasive computing effort is proceeding in two phases.

In phase 1, we are prototyping experimental smart spaces. The prototypes focus on advanced forms of human-computer-interaction, integrating pico-cellular wireless networks with dynamic service discovery, automatic device configuration, and software infrastructures required to successfully program pervasive computing applications. The objectives of phase 1 are to:

- Identify key areas which would benefit from standardization, e.g., service discovery, APIs, and interoperability,
- Provide 'hands-on' experience in identifying applicable measurements, e.g., conformance tests, interoperability tests, diagnostic tools, and benchmarks, to promote the technology,
- Identify security mechanisms needed to ensure privacy, integrity, and accessibility of implementations.

In phase 2, they are:

- Develop metrics, test methods, and standard reference data sets to 'pull' the technology forward,
- Provide reference implementations to serve as models for possible commercial implementations,
- Collaborate with industry standards groups to develop unambiguous, testable specifications,
- Establish partnerships with industry and academic organizations,
- Interconnect the phase 1 prototypes to explore key issues associated with distributed smart spaces.

2. Background

Smart Spaces are work environments with embedded computers, information appliances, and multi-modal sensors allowing people to perform tasks efficiently by offering unprecedented levels of access to information and assistance from computers. Smart Spaces support stationary and mobile information environments that may be connected to the Internet. Companies are producing various portable and embedded information devices, e.g., PDAs, cellular telephones, and active badges, for mobile information environments. Concurrently, wireless technologies, including Bluetooth, IrDA, and HomeRF, will outfit these devices with high bandwidth, localized wireless communication capabilities to each other, and the globally wired Internet. The emerging network of the future includes small, specialized devices roaming among islands of wireless connectivity within a global ocean of wired networks. The islands are Smart Spaces, where services and embedded devices are discovered, accessed, and interconnected with portable devices carried into the spaces. Then the combination of imported and native devices can be exploited to support the information needs of the current island inhabitants. Mobile and stationary Smart Spaces may identify and perceive users, their actions, and even goals; facilitate interaction with information rich sources; provide extensive presentation capabilities; anticipate user needs during task performance; increase information interchange rates; provide improved records and summaries for later use; and support distributed and local collaboration. This picture is no longer fiction, but an imminent reality; once a number of challenges have been mastered.

3. Challenges Facing Industry

Companies, ranging from small innovative startups to larger traditional IT organizations, are embracing pervasive computing and producing a myriad of new products. The majority are focused on near-term needs, i.e., on development and use of information appliances – devices with computational capabilities used for specific applications – and the issues of getting them connected to the Internet through wireless and wired links. A large number of constituent technologies, too many for any single company to address, must be integrated in Smart Spaces. Issues of integration, interoperability, performance, and security are concerns; but for many companies, not yet primary objectives. Due to resource limitations and pressure to be first to market, many companies narrowly focus on a few pervasive computing technologies, rather than the boarder issues of integration, interoperability, and performance. Figure 1 illustrates some of the technologies needed to create smart workspaces, and their interdependencies.

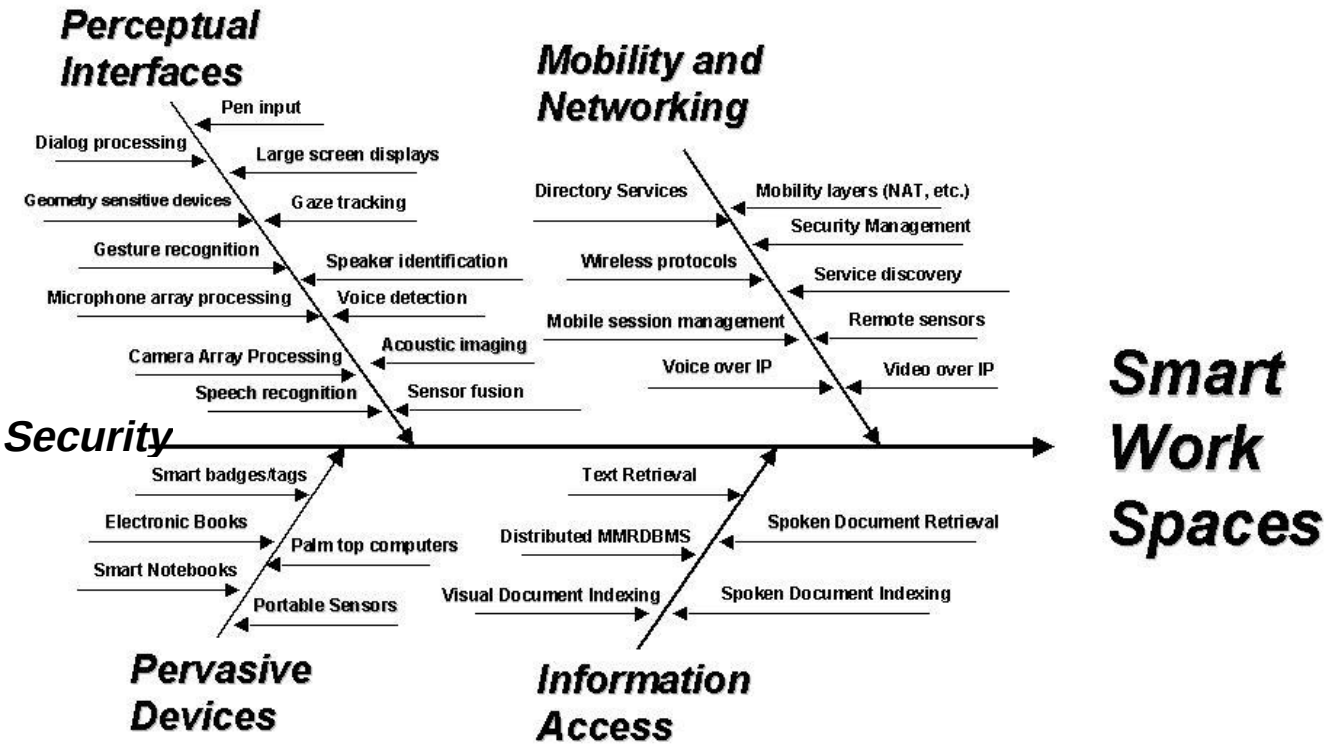

Figure 1. Some examples of pervasive computing technologies for integration into Smart Work Spaces

To foster integration, interoperability, and the development of emerging technologies, standardization and measurements are critical, but for economic reasons, often are not addressed by individual companies. The lack of common software infrastructure, tools to create, manage, measure, test, and debug pervasive services, standards in key areas such as service discovery, APIs, pico-cellular wireless networks, automatic configuration, and ad hoc transactional security, all currently impede widespread adoption of pervasive computing. Also, measurements and tests developed and performed in a public forum allow competing research systems to be compared, and improved systems to be built on the best features of previous iterations.

4. Requests from Industry

At the October 1999 Jini[1] Technology Community Meeting, attended by over 200 stakeholders in pervasive computing, a survey of projects, including a technology Wish List, was conducted. Companies including Sun Mircrosystems, Xerox, Motorola, cOcO Technologies, Oki Data Americas, and Amiga, asked for:

[1] Jini™ from Sun Microsystems, is a software infrastructure based on Java™ technology that enables all types of devices to simply connect into impromptu networks, making access to and delivery of new network services as simple as plugging in a telephone.

- Standardization of testing and diagnostic tools,
- Security assessments and capability-based security,
- Interoperability among diverse applications, services and devices,
- Standardization of APIs,
- Reference implementations and standard reference materials,
- Improvements in robustness and software quality.

Industry and academic experts have indicated that ITL would be most effective by playing its traditional role in measurements, testing, and standards. In interviews R&D engineers suggested that ITL should aid the pervasive computing community by developing appropriate tasks and benchmarks for smart spaces, as well as reference data sets, measurement tools with generalized interfaces to experimental databases and a web site with pervasive computing information. Additional requests for ITL assistance in developing measurements, tests, and standards were also received, including:

- The Biometrics Consortium requested ITL to help develop APIs for biometrics-based systems,
- The Bluetooth Consortium requested ITL to help develop abstract test suites for the Bluetooth system (i.e., RF communications standard) and formal models of Bluetooth protocols to verify that the specifications are complete, unambiguous and free from deadlocks and livelocks,
- IEEE 802.15 Working Group on Wireless Personal Area Networks requested ITL to study the coexistence of IEEE 802.15 devices (e.g., Bluetooth and HomeRF) with each other and with devices in the unlicensed 2.4 GHz ISM band (e.g., wireless LAN systems and microwave ovens),
- GTE-BBN, IBM, HP, and Kaiser Permanente requested ITL to help develop performance evaluations of technologies, measurement tools, and to help define what data should be collected, annotated, and used to measure performance,
- Over 60 companies, including AT&T, GTE/BBN, GE, Harris, IBM, Lexis-Nexis, and TextWise, requested ITL to continue efforts to evaluate text retrieval technologies.

5. ITL's Role

Although many companies understand the value of working together on generic, pre-competitive technologies, it is not economical for them individually to develop standards, metrics and tests. Also, most universities engage in research and education, rather than develop metrics and tests. Even if industry or academia develop metrics and tests for their own products and systems, they would not push the technology in the way large-scale evaluations do, since they would not compare a wide range of systems. Furthermore such metrics and tests might be biased toward the products of the companies involved, and would not be trusted. NIST/ITL has earned a reputation for objective, impartial measurements, tests, and for high quality technical competence that instills trust in ITL's products. ITL measurement tools and techniques have achieved wide recognition and use in the United States and internationally.

To better understand the technical, standardization and measurement issues involved, ITL has taken a four-pronged approach:

1. **Interacting with Industry**. ITL is sponsoring an ongoing series of conferences on pervasive computing. These bring together companies, academics, and non-profit organizations engaged in

research, planning, and development of pervasive computing products, services and applications to provide a forum for discussions, demonstrations, projects, and issues. The Pervasive Computing 2000 Conference, held January 25-26, 2000, attracted major industry experts, (e.g., Bill Joy, Sun Microsystems, Craig Mundie, Microsoft, David Nahamoo, IBM, Tobin J. Lehman, IBM) and was very productive and well attended, despite the blizzard weather conditions. Additionally, ITL staff participates in conferences by presenting papers and demonstrations, e.g., Usenix and JavaOne Conferences, as well as meeting with industry experts to discuss potential collaborations, e.g., Kaiser Permanente, DARPA.

2. **Developing Prototypes**. ITL has established two projects focused on the development of prototype implementations (test beds) to gain competence, industry recognition, and identify the standardization and measurement issues in pervasive computing. The Software Diagnostic and Conformance Testing (SDCT) Division and the Advanced Network Technologies Division (ANTD) have joined together to develop the AirJava/Aroma prototype. This project focuses on the software infrastructure and networking aspects of pervasive computing. The Information Access and User Interfaces (IAUI) Division is developing a Smart Space Modular Test Bed which is focused on advancing human-computer interfaces and information access in environments embedded with computers and sensors. Appendix A contains brief descriptions of these prototypes. Although they are separate projects, there is a great deal of synergy between them and efforts are under way to coordinate goals, reuse software, solutions, and share expertise. As these projects mature, it is likely that a hybrid, combining features of both will be developed and expertise from other ITL Divisions, e.g., Computer Security, will be incorporated. They also provide measurement platforms for industrial technologies. Future prototypes will serve as reference implementations and be done in collaboration with other NIST Laboratories as well as with industry partners.

3. **Participation in Standardization efforts**. Working with industry, ITL participates in open, consensus-based standards forums such as Consortia, IEEE, and ISO/ANSI organizations to develop testable standards/specifications for emerging technologies. ITL is participating in several activities for pervasive computing: IEEE 802.15 Wireless Personal Area Networks, Bluetooth Consortium, HomeRF Consortium, NCITS R1 Real Time Systems, Jini Community Development Process, and IETF Zero Configuration Working Group. ITL continues to explore opportunities to participate in the development of new pervasive computing standards. ITL will take a leadership role in helping to identify and develop standards and specifications in areas where standards facilitate the acceptance of pervasive computing, e.g., service discovery, APIs, automatic configuration, and ad hoc transactional security.

4. **Participation in Measurement and Testing Efforts**. The activities and outcome from industry interactions, prototypes, and standardization efforts will drive ITL efforts in developing measurements and testing approaches (e.g., metrics, reference data sets, diagnostic tools, abstract test suites, and conformance tests) to advance pervasive computing. For example, ITL is working with industry to define test scenarios, tasks, and to develop an integrated architecture for human-computer interaction in Smart Spaces.

Some of the initial ITL accomplishments and products produced as a result of our approach include:

- **Software quality** – develop software tools and tests to help ensure the quality and 'correctness' of pervasive software infrastructures and applications; e.g., Jini Services Scripting is a tool that makes it easier to install and deploy Jini services, by insulating the programmer from the necessary low-level software manipulations, and thus maximizing consistency and minimizing chances for errors,
- **Networking of Smart Spaces** – integrate various aspects of network communications and services to provide a networking environment that is easy to use and intelligent; e.g., AirJava, a reference implementation, that provides network discovery, self-configuration, and service discovery for a device in a dynamic-hybrid network environment and thus, provides industry with both 'proof-of-concept' model they can mimic or build upon,
- **User interfaces** – design of standard test materials and systematic metrics for areas like spoken language and biometric person identification to achieve intuitive user interactions; e.g., Multi-channel spontaneous speech data synchronized with video data will provide industry with reference data in a conference room scenario, such as an intelligent medical examination room.

In support of this four-pronged approach, other projects within ITL Divisions are also relevant to pervasive computing. Table 1 shows topics on which the ITL is currently working. Specific names of companies and other organizations involved in this area are also provided.

Topics	Technologies	ITL Role	Companies
Wireless Communications	Wireless telephony systems: W-CDMA & cdma2000	Performance evaluation and development of software testbeds	Int'l Telecom. Union, Qualcomm, Ericsson, European Telecom. Standards Institute
Pico-cell Wireless Systems	Bluetooth, MANET	Conformance and Interoperability testing; Protocol modeling & verification; Performance and coexistence evaluation	IBM, Intel, Ericsson, Nokia, Toshiba, SAIC, Raytheon, Mitre, SRI
Real-time System & Communications Protocol	Java/Jini	Help develop requirements for real-time Java; Performance metrics & tools	IBM, Microsoft, HP, Honeywell, Motorola, Nokia, Sun, SoftPLC, Siemens, etc.
Speech Understanding	Transcription, information extraction, topic detection & tracking, spoken document retrieval	Benchmark tests; Common test sets; Uniform scoring	AT&T, GTE/BBN, Dragon Systems, IBM, Claritech, GE, SRI, Philips
Interactive Dialogue	Speech-based dialogue	Develop metrics; Develop tests	MITRE, AT&T, GTE/BBN, CNRI, Hughes, IBM, Intel, Lockheed Martin, Lucent, Microsoft, Philips, etc.
Person Recognition	Speaker recognition, face recognition	Benchmark tests; Common test sets; Uniform scoring	GTE/BBN, Dragon Systems, ITT, SRI, Aegir, Excalibur, TASC
Multi-media Information Extraction	Text retrieval, web searching, question answering, interactive retrieval	Develop metrics; Develop test data; Uniform scoring	AT&T, GTE/BBN, Claritech, Lexis-Nexis, TextWise, IBM, Microsoft, GE, Harris, Fujitsu, etc.
Security	Cryptographic testing	Testing/Validating cryptographic modules	IBM, Entrust, Netscape, Motorola, nCipher, IButton, GTE, Cylink, SPYRUS, etc.
Biometrics	Biometric authentication, biometric system interoperability	Standards development & testing	Compaq, IBM, Microsoft, Novell, Miros, Identicator, Veridicom, etc.
Electronic Book	E-Book content, interoperability	Standards development & testing; Interoperability standards	Softbook, Nuvomedia, Librius, EveryBook, Microsoft, IBM, Adobe

Table 1. ITL Projects related to pervasive computing

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Any mention of commercial products within NIST papers is for information only; it does not imply recommendation or endorsement by NIST.

APPENDIX A: Prototype Descriptions

AirJava/Aroma
http://w3.antd.nist.gov/~mills/projects/AirJava/
http://www.itl.nist.gov/div897/ctg/aroma.html

The AirJava/Aroma project focuses on creating and studying the network and software aspects of a wireless, Jini-based smart space. The aim of this project is fourfold – to discover technical, measurement, and standards issues related to: (1) connecting portable wireless devices to traditional networks, (2) service discovery, self-configuration and dynamic resource sharing, (3) mobile code and data, and (4) software infrastructure needed to create and manage pervasive services and applications.

The initial research challenge was to design an ***AirJava*** adapter that can convert existing computer-controllable devices into prototype Smart Space devices. Such a device has been designed and constructed and is capable of running a Java Virtual Machine and Java-based distributed computing software such as Jini and JavaSpaces, communicating wirelessly to a Jini server and to peer devices, and connecting to a range of computer-controllable devices. The AirJava adapter will be used to implement a simple research information appliance using a digital projector to create a wireless, discoverable projector service.

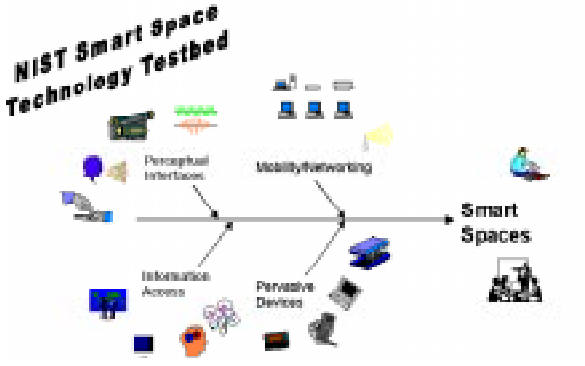
The nature of pervasive computing will require that we research and develop the needed software prototypes, infrastructure, and tools to allow us to experiment with, debug, test, measure and manage the pervasive clients and services. We plan to explore the following areas:

- Various means of implementing pervasive services and clients including Java-based, non-Java-based and hybrid architectures,
- Java and native-based service browsing, diagnostic, debugging and testing tools,
- Pervasive service metrology,
- Pervasive service software infrastructure and “bootstrapping” code,
- The use of low computational-power devices as clients and servers,
- Lightweight OS and OS-less services using tools such as the Flux project’s OSKit.

We plan to collaborate with other NIST, industry and academic groups to leverage resources, ideas and results from each group’s efforts. Our software will be in the public domain for use by others and will be used to guide our participation in the standards process. As we tackle some of the research objectives related to pervasive computing, we will begin to identify requirements that will ultimately drive longer-term software and networking research and standards work at ITL. We will make the design for *AirJava* adapters available to other researchers outside NIST, so that those researchers can use or improve them. In addition, lessons learned in designing and constructing the adapters might also be of use to industrial designers.

SMART SPACE MODULAR TEST BED

http://www.itl.nist.gov/iaui/iaui/presentations/Smtspaces-darpa1/index.htm



Working with numerous industrial and academic R&D institutions, ITL has played a leading role in metrics research in speech recognition, information retrieval, and natural language query generation. The aims of this project include: (1) Establish an integrated multi-sensor perceptual interface test bed for smart work spaces. (2) Support integration of the AirJava/Aroma components. (3) Deploy perceptual interface components from our industrial advisors to investigate system level performance and metrics issues. (4) Provide a multi-sensor data recording environment for the production of standard test materials.

We are developing the Smart Space Modular Test bed, which consists of a defined middleware API for real-time data transport, a connection broker server for sensor data sources, and processing data sinks. For example, a microphone array acquires a speech signal, reduces it to a single channel, and offers it as a data-flow. Then a speaker identification system subscribes to the signal flow, while a speaker-dependent speech recognition system subscribes as well. The speaker ID system then offers a real-time flow, to which the speech recognition system also subscribes. This layer makes it possible to integrate components that were not intentionally designed to work together, such as speaker identification and speech recognition systems. Many constituent technologies are under separate development in industry, so the issues of interoperability and integration are paramount. This project will develop metrics and reference material based on real implementations for industrial use. Important technologies include sensor-based collaborative interfaces using:

- Speech recognition
- Speaker identification
- Face recognition
- Source localization/separation
- Channel normalization
- Immersive video and acoustic displays
- Personal information appliances
- Pervasive networking
- Information storage and retrieval
  - multimedia data types
  - object-encapsulated
  - active data
- Multiple Interconnected Spaces

Impacts

- Increased ability to interact easily with computers, especially collaboratively.
- Ability to help set standards and metrics in sight and sound based information intensive interfaces.
- More facile information retrieval and integration of greater information content, with integration into interfaces of the future.