Ubiquitous Computing Infrastructures

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The Distributed Systems Group conducts research into distributed software infrastructures, networks of embedded devices, and novel interaction paradigms.

Of particular interest is the field of *ubiquitous computing*, which aims to make computers available throughout the environment, while rendering them effectively invisible. One specific goal is to incorporate computing power into everyday objects in order to create "smart things": real-world objects that provide novel ways of accessing information, react to their environment, or provide new emergent functionality when interacting with other smart things.

This vision of ubiquitous computing is grounded in the belief that microprocessors and advanced sensors will soon become so small and inexpensive that they can be embedded into almost anything. It is expected that billions of such objects will be interwoven and wirelessly interconnected to form an *Internet of Things*, a worldwide distributed system several orders of magnitude larger than today's Internet.

To enable communication and cooperation among smart objects, new information infrastructures are required. They will have to cope with a highly dynamic environment and should, among other things, provide location information to mobile objects, represent context information, and enable reliable and scalable service creation. The Distributed Systems Group addresses the challenges of designing and implementing such infrastructures.

Software Infrastructures. Application development for ubiquitous computing relies on software frameworks that provide higher-level abstractions. With *Fosstrak,* we are developing an open-source software platform that facilitates business process automation using Radio Frequency Identification (RFID) technology to automatically track and identify individual product items in the supply chain. Fosstrak is implementing an open specification to which we are contributing key concepts such as an event specification language and an abstraction layer for RFID reader devices. A second line of research is concerned with *Location Oriented Programming*. Driven by the observation that location is a key concept in ubiquitous computing, we are exploring techniques to make location a first-class programming construct. This entails the creation of models, language constructs, and supporting architectures, such that location-based relationships and trajectory-based aspects are easily assessed, accessed, and processed.

Sensor Networks. We anticipate that wireless networks of autonomous computing devices, each equipped with sensors, a wireless radio, and a processor, will be deployed unobtrusively in the physical environment in order to monitor a wide range of environmental phenomena. These networks will be of an unprecedented quality and scale. The close integration of such sensor networks with the physical world presents a number of challenging research problems.

We are investigating these research questions within the framework of NCCR MICS, the National Center of Competence in Research on Mobile Information and Communication Systems. In an early phase of MICS, we jointly developed the *BTnode system* together with other research groups at ETH Zurich. This system is a hardware and software platform for sensor networks that forms an important experimental environment for validating and evaluating our research.

More recently, we have been studying *novel programming paradigms* to mitigate the complexity of sensor networks resulting from constrained resources and large, dynamic network topologies. In particular, we have been devising declarative specification techniques to program a sensor network as a whole at a high level of abstraction. We have also been investigating concepts and tools for facilitating the *deployment* of large-scale sensor networks for realistic applications. Motivated by the fact that in practice many sensor network deployments fail even though they have been extensively tested in the lab, we are developing mechanisms for in-situ monitoring, debugging, and managing sensor networks on the deployment site. In addition, we are investigating practical algorithms for reliably and efficiently gathering data from sensor networks. To validate our approaches, we are also working on concrete *applications* such as a sensor network for monitoring noise pollution in urban environments. We are contributing our experience in this area to several projects funded by the European Commission.

Internet of Things. By extending the Internet to reach out into the physical world, an Internet of Things emerges that globally interconnects smart objects and sensor networks. To this end, *mobile phones* are a key technology serving as

Fig. 1. Fosstrak: an open-source software infrastructure for business process automation.

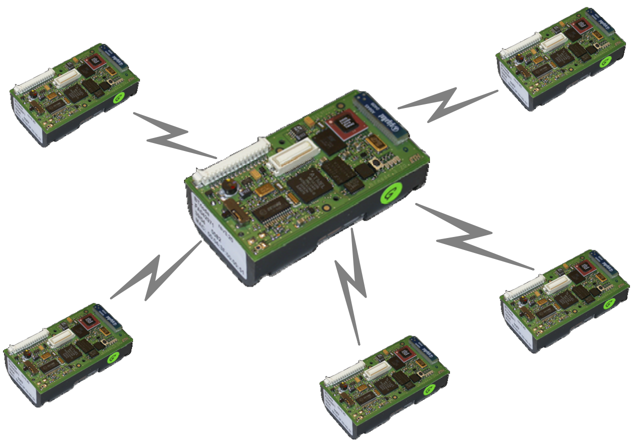

Fig. 2. BTnode: a hardware and software platform for sensor networks.

ubiquitous gateways to smart objects and sensor networks embedded in the environment. In cooperation with leading telecommunication companies, we are exploring the use of mobile phones as a building block for the Internet of Things. In one such project, we are using mobile devices as people-centric sensors and as a gateway to sensor networks embedded in the environment, thus gaining online and real-time access to the state of real-world objects and environments. Building on this infrastructure, we are investigating approaches to enable *real-world searches* for objects that exhibit a certain state at the time of the query – a challenging problem due to the scale and dynamics of the information space being searched. In a related project called *Phacebook,* we are investigating how people-centric information collected by mobile phones can be integrated into social networking platforms such as Facebook, so that the resulting system can make recommendations to users, taking into account the current location and activities of other people with similar interests.

Interaction with Smart Environments. Novel forms of interaction are required to allow humans to interact with smart objects and environments. Again, mobile phones are considered a key technology due to their ubiquitous deployment and user acceptance. In the *BaToo* project we are investigating the use of camera-equipped mobile phones for the robust scanning of bar codes, addressing the challenges presented by realistic environments such as imperfect illumination and blurred images. Based on this approach to product identification, we are exploring novel services and interaction techniques by linking products with the abundance of product-related information available on the Web. We are also studying novel interaction paradigms in *augmented toy environments*, where traditional toys such as a knight's castle are augmented with sensors and actuators to enrich children's play by sound effects, verbal commentary, and visual feedback. This also allows us to integrate an *interactive learning experience* into play. Beyond the design and implementation of such augmented toy environments, we are performing user studies in cooperation with social scientists in order to evaluate the impact on children's play.

Fig. 3. Robust scanning of bar codes with camera-equipped mobile phones.

Implications of Ubiquitous Computing. Ubiquitous computing technologies will have a strong impact on future society. In a project funded by the Gottlieb Daimler and Karl Benz Foundation, we collaborated with an interdisciplinary group of researchers to analyze its social, economic, and legal implications. In particular, *security and privacy* will be of prime concern in a world of highly interconnected, invisible devices that will eventually permeate our everyday lives. We are therefore exploring privacy awareness concepts targeted at ubiquitous computing environments that allow data collectors to both announce and implement data usage policies, as well as providing data subjects with a technical means of keeping track of their personal information as it is stored and used.

Business Applications. The *M-Lab*, a joint venture with the University of St. Gallen, was created to bring the ideas of ubiquitous computing into companies that could benefit from the availability of smart devices, radio frequency identification, and related technologies. In the past, we have focused on areas such as logistics, retail, and the automotive sector – bringing together researchers from academia and practitioners from industry in order to contribute to the research area and create competitive advantages. In the *Bits to Energy Lab*, a recent spin-off from the M-Lab, we are exploring the use of ubiquitous computing technologies to increase the transparency of the ecological footprint of economic and industrial processes, products, and services. In particular, we are investigating the applicability of sensor and actuator technologies for increasing energy efficiency in production and logistics, and also exploring new ways of influencing user behavior. Finally, we are analyzing the impact of such technologies on enterprises.

Teaching. Besides teaching the fundamentals of distributed systems, distributed algorithms, and Internet technology, our graduate level curriculum focuses on state-of-the-art concepts in ubiquitous computing. Lectures are accompanied by hands-on programming experience. In-depth seminars allow students to individually research and present fundamental works in the field, as well as investigating recent developments. In our Ubicomp Lab, students can devise and build their own smart environments using handheld devices, sensor networks, RFID, and wireless communication equipment such as Bluetooth, Zigbee, and WLAN.

Fig. 4. Interaction with augmented toy environments.