ContextExplorers: mobile agents for run-time context discovery, validation and verification

We are witnessing an unprecedented use of the Internet, communication and computing technologies in commerce, business, government, health, defence and educational applications. Software solutions help to improve the efficiency of businesses, and to manage and exploit the information explosion. Advances in software technology, ubiquitous devices and the increasing volume of digital knowledge offer the opportunity for more sophisticated and user-friendly electronic services. Mobile software agents represent one of recently emerged paradigms related to pervasive computing that carry a tremendous promise in solving some of the real world problems and enabling "anytime, anywhere, with any device" access to digital information and services. Context-awareness and context management are in the focus of intensive ongoing research efforts by the pervasive computing research community.

Pervasive computing is a computing paradigm incorporated in a variety of devices (computers, cars, entertainment units, appliances, etc.), which can carry out computing in a relatively non-intrusive manner and can impact and support many aspects of work and everyday activities. Pervasive systems need to be aware of their environment and available resources (i.e. aware of their context), able to detect changes in the environment (context changes) and can adjust/adapt their functionality and behaviour to the changes. Context information (description) includes specification of user and application requirements as well as measurements of quantifiable entities in the environment. The main difficulty in building pervasive systems is their complexity as their problems (and solutions) belong to many converging research areas like mobile networks, mobile distributed processing, theoretical computer science, agent technology, human-computer interfaces, reflection in computer systems and component software engineering. Due to this complexity current approaches mostly tackle particular problems (e.g. adaptation of web content to a variety of displays in mobile devices or adaptation to varying communication bandwidth) and do not provide general models for pervasive systems. Therefore, there are no frameworks, which allow both reasoning about properties and functionality of pervasive systems and manipulating these properties and functionality with software tools like agents. Pervasive computing systems represent a natural extension and evolution of mobile/ubiquitous/nomadic computing systems, which first emerged in early 90s [Mobility 1999; Abowd 2000; Zaslavsky 1998a; Deitel 2002; Kindberg 2002]. These systems have come a long way relatively quickly due to research on many issues, including power efficiency, disconnected transaction management [Rasheed 1997], itinerary algebra for mobile agents [Loke 2001a], ambient calculus [Cardelli 2000], as well as complex issues of context description and application adaptation [Efstratiou 2001; Noble 1997; Nzama 2001], component based distributed systems [Mobility 1999; Cuce 2002; Loke 2000] and reflection techniques to carry out adaptation [Indulska 2001].

Some early models of pervasive computing have already emerged [Harter 1999; Banavar 2000] though there are many remaining research challenges. As far as context description and context-aware computing are concerned, existing approaches have two main drawbacks. Firstly, they target only a subset of context information like location of persons and devices (Sentient Computing [Harter 1999], Guide project [Cheverst 2000]), device capabilities [Suryanarayana 2001], context information related to quality of communication (e.g. network bandwidth), (context information gathered by operating system resource monitors which track resources such as CPU, memory and bandwidth (Odyssey [Noble 1997]). There are also approaches to capture application requirements and user requirements and some relationships between devices, users and software components [Spriestersbach 2001; Loke 2001a; Loke 2000; Zaslavsky 2002b]. Secondly, the existing approaches to context description fail to capture dependencies between context information leading to autonomous adaptations based on partial information, which therefore can negatively impact the

behaviour and functionality of the remaining part of the system. Moreover, they can lead to cascading adaptations, as there is no coordination of adaptations and impact analysis in the system.

A relatively recent computing paradigm is software agent technology [Mobility 1999; Loke 2001c]. Agents refer to software that exhibit intelligent behaviour and certain autonomy, i.e. they are characterised by flexibility not usually found in traditional software systems. The behaviour of software agents is such that human intuition assigns to them qualities such as autonomy, communicative ability (with other agents or people), pro-activity, adaptability, reactivity, rationality, and mobility (from one machine/environment to another). Building software systems with such sophisticated qualities is non-trivial and, while in the midst of much commercialisation, is very much a thriving area of research. Agent technology continues to mature with the establishment of the Foundations of Intelligent Physical Agents (FIPA) (http://www.fipa.org) which issues standards that specify the agent system architecture and inter-agent communication systems. Agent technology has already found substantive applications in monitoring distributed systems [Hart 2001; Moro 2000], in scheduling and itinerary construction {Loke 2001], web services [Brebner 2002; Papastavrou 1999; Klusch 2001], in telecommunication applications [Baumann 2000]. Agent technology based systems have also been built to provide various web-based services [Klusch 2001]. These vary in scope of services provided and sophistication of technology employed. The value that agent-based systems can provide over traditional information Web portals (e.g., www.financewise.com) and traditional expert systems include proactive, autonomous, and contextualised (sensitive to the user's profile, the user's current needs, available information and current world situation) behaviour. We believe that these are important and very useful characteristics for current and future web-based services.

The efficiency of using mobile agents in enterprise applications is argued in [Papastavrou 1999; Zaslavsky 1998; Loke 2001c]. Indeed, mobile agents can not only be used for what Remote Procedure Calls (RPCs) have traditionally been used for, but also offer a number of advantages [Gray 2000], such as reduction of bandwidth utilization by moving computation to where the data is in contrast to moving large amounts of data around, reduction in total completion time of tasks by encapsulating multiple queries (e.g. to databases) in an agent, thereby reducing the amount of communication between clients and servers compared to using RPCs, load balancing by moving computational load to available resources, and flexible dynamic deployment of components by moving code (in the agent) to where they are needed as needed. For mobile environments, agents can be launched (not necessarily from the user's current device) to perform tasks without maintaining an expensive unreliable wireless network connection. Recent studies have already addressed using software agents for context discovery [Arcos 2001; Jun 2000]

Our project is to further research into context-aware software agents that are capable of enhancing functionality of pervasive computing systems, deliverable over the Web and the mobile/wireless services on the Internet. Also, we seek to apply current advancements in agent technology and pervasive context-aware computing to web-based services.

This project, named **ContextExplorers,** will investigate and develop methods and tools that will generate mobile software agents and inject them into the network. These agents will be capable of discovering and sensing the current context in which a monitored pervasive computing system is running, validating and verifying the context attributes via direct and indirect techniques and then communicating the discovered and verified context back to the target application or a mobile object. Examples of context attributes include network bandwidth, location, temperature, and presence of light or sound. Context variables also include spatial and temporal attributes. The software agents will migrate from one computer to another, reproducing cloned agents for more efficiency, coordinating their activities, and making use of general purpose devices like network adapters, microphones or video-cameras, or specialised sensor devices like light sensors or thermometers. In

certain cases, these agents might even exhibit proactive behaviour and initiate events, like switching the lights on in a dark room.

While authentication and verification of the object or a person behind the device interface is a problem for any application, be it wired or wireless, it takes on higher priority and urgency for wireless and/or mobile applications. The argument for that is the greater delegation of decision making and inherent time pressure for users who are mobile. Greater reliance on and/or proliferation of mobile agent technologies combined with granting those software agents greater autonomy and independence makes imperative the development of direct and indirect techniques that can assure users about the identity and authority of their software interlocutors. What are the guarantees that the person who participates in a videoconference is not a software impersonation? Is it not tempting, given increased workload and responsibilities, to have an unlimited number of specialized software clones of self which could take on routine and seemingly unimportant activities delegated by the user? How to combine these virtual and real worlds in a pervasive computing system? What are the privacy and security issues that might arise?

The focus of this project is also aligned with a PhD project, which will look into context algebra and the ability of agents to extract context attributes, classify those and identify attributes that need validation and verification. The target users of the ContextExplorers system are groups or individuals requiring specialised pervasive application services. Imagine a scenario of a user Jack who happens to be an academic and walks from his/her office towards a classroom to give a lecture. Such a scenario is illustrated in figure 1. Let us assume that computing will have become invisible and ubiquitous, that is, discoverable interfaces and computing devices are all around us, embedded and integrated into the surrounding environment. A community of mobile agents is injected into the network and they follow, or rather precede Jack. These software agents, that can clone and self-destroy, discover the route that Jack is taking; identify available resources they can use for computations; identify sensors for reading physical context attributes; discover context attributes, including spatial and temporal parameters; analyse and manipulate with discovered attributes in order to identify those that are susceptible to validation and verification; attempt to foresee the developments and impact; generate compensating or neutralising events; and fulfil the mission they were charged with. For example, an agent can check whether the light in a room on the way is on. Even if the context attribute value conforms to the "on" condition, the agent may decide to verify this attribute and via a light sensor double-check this attribute. If discrepancy between the values is found, third test is performed and additional light will be switched on. Examples could include checking video equipment status, reported location, status of air-conditioning systems, presence of students, etc.

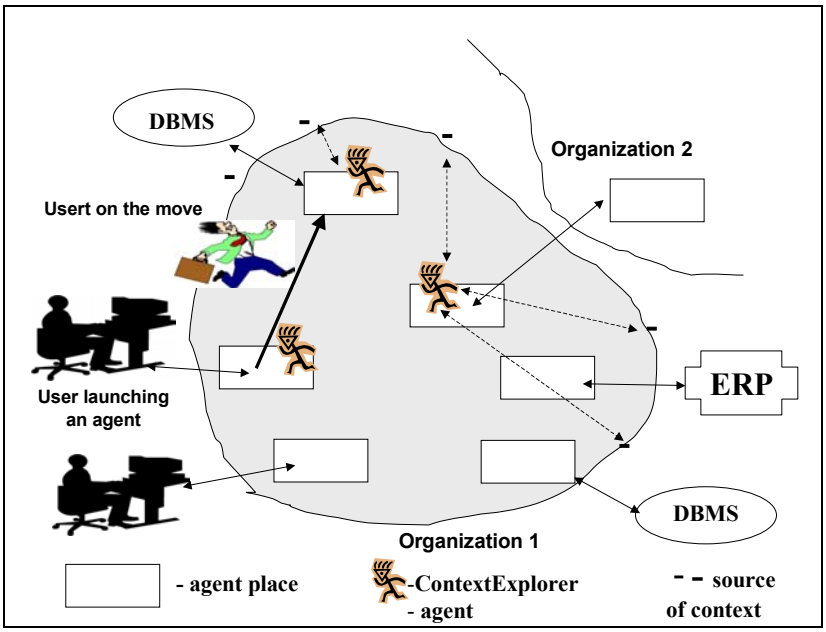

Fig.1. ContextExplorers agent community

The major **questions**, which this project will address include:

- How do we achieve flexibility and efficiency of distributed middleware services in enterprise environment using mobile software agents and emerging standard platforms and environments like FIPA?
- What are the properties of existing and future agent platforms to support context-aware applications?
- How these technologies, platforms and environments can be extended in order to become more usable, application domain oriented and efficient though sophisticated?
- How to discover current context, classify it and analyse it for consistency, dependencies, credibility and how to pass that knowledge on to software mobile agents?
- What are the security and privacy implications of substantial opportunities to potentially track and observe any physical or virtual object with mobile agents?

Important **aims** include:

- To evaluate existing mobile agent technologies, platforms and their level of support for run-time context discovery, context attribute validation and verification and propose a comprehensive taxonomy of these technologies;
- To develop a conceptual architecture for the ContextExplorers system that will support efficient software agent-based services to end-users, identify the stages in implementing this architecture and focussing on core components of the proposed architecture (see figure 2). Of particular interest is the context handling engine and analyser to check for consistency, dependability and cross-impact of context attributes. This component will be researched, developed and prototyped in the course of the proposed PhD project.
- The algorithms, prototypes and components to be developed for the project will be innovative and will make a tangible contribution to the field of mobile agents in pervasive enterprise applications. More specifically, the emerging mobile agents paradigm will be investigated and the core components developed and prototyped. Whenever possible we leverage on the work already done by the applicants [Loke 2001; Loke 2000; Loke 2001b; Loke 2002; Stanski 1998; Zaslavsky 2002a], but will need to develop novel complementary technologies.

The conceptual architecture of the proposed ContextExplorers system is illustrated in figure 2 below. The main modules include User Manager, Context Handler/Manager, Mission Generator, Context Analyser, Agent Control Centre, Security & Privacy Manager, and Knowledge Integrator (is currently outside the scope of this project). Research challenges addressed in this project are related to these components.

Specific aims of this project are:

- To evaluate and analyse recently emerged mobile agent technologies and their level of support for handling context, including run-time discovery of current context, analysis of context attributes, validation and verification of context attributes. The project will look at various aspects of these technologies including openness, flexibility, interoperability, portability, cost-efficiency, adaptability, customisation and extensibility.
- To explore the classes of enterprise web-based services that have to be context-aware and where mobile agent technology could be useful, efficient and flexible.
- To develop and prototype the core components of the proposed architecture. In particular, the following component will be developed, prototyped and prepared for possible commercialisation by the industry partner:
  - *Context handling engine based on mobile agents*. This engine is intended as a generic software layer built on top of standard agent frameworks, like FIPA. Current work has not explored the potential of mobile agents for run-time context discovery and analysis. We intend to develop context algebra and extend the itinerary algebra [Loke 2001a]. From applications' point of view, their context C can be divided into the internal and external

context C ={C_i, C_e}. External context captures both requirements (acceptance regions for context values) and current context of resources, interactions and services: C_e={C_{env}, C_{user}, C_{device}, $\Re$}, where C_{env} - context describing application's environment and application's requirements; C_{user} - user context related to the application; C_{device} – device context for the device currently used by the application; $\Re$ - context relationships. The architecture for management of current context is usually hierarchical and its levels are respectively responsible for context gathering (from a variety of hardware and/or software sensors), context interpretation (which may involve complex processing of raw sensor data) and context description (the final context description represented in a general form readable for the system). Context sensing and interpretation methods depend on the type of context and are reasonably well understood for many types of context. In our research we concentrate on the context description and manipulation by software agents as this level is still poorly defined but it is crucial for building pervasive systems. As can be seen from the description of context scope, the context description falls into an N-dimensional space, which we call *context space* [Zaslavsky 2002a], where N is defined by the number of various context aspects: $C = (c_1, c_2,\ldots,c_N)$, $c_i \in C_{env} \vee C_{user} \vee C_{device}$ where each c_i is a context attribute (name-value pair) and can be represented as a complex data structure [Zaslavsky 2002b]. Context attributes can be independent (a change in the attribute does not have any impacts on other context attributes) or dependent. There are some early approaches which try to take dependencies between context information into account like [Efstratiou 2001] which considers dependencies between bandwidth and battery power in applications adaptations, [Noble 1997] which uses a centralized 'warden' for each resource being adapted (operating system resources) and therefore is able to coordinate adaptations among applications for this particular resource (but not between resources).

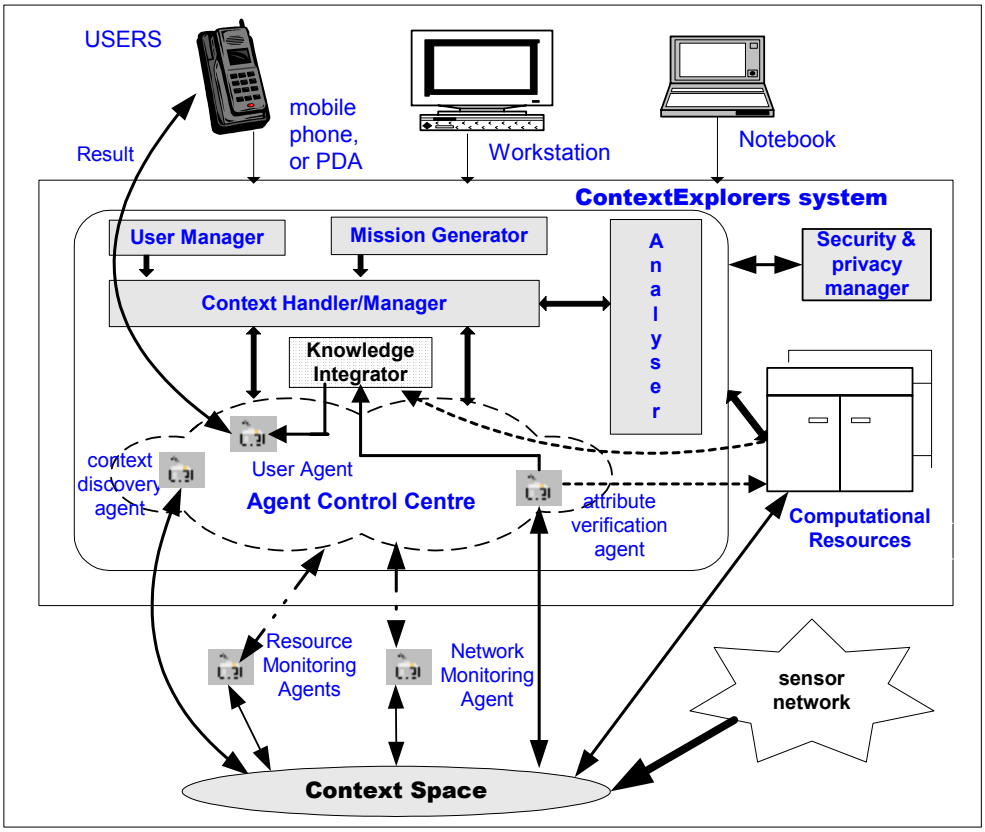

Fig.2. ContextExplorers architecture

- To develop and prototype an architecture integrating the above ideas and components, juxtaposing the architecture with the Web and the mobile Internet (e.g., WAP

(http://www.wapforum.org)); we shall exploit current work on the agent standards provided by FIPA which provide details on agent management and consider existing toolkits built on FIPA standards.

REFERENCES

[Abowd 2000] G.D. Abowd and E.D. Mynatt, "Charting Past, Present, and Future Research in Ubiquitous Computing", ACM Transactions on Computer-Human Interaction, Vol. 7, No. 1, March 2000, Pages 29–58.

[Arcos 2001] J. Arcos and E. Plaza, "Exploiting context awareness in information agents", Proceedings of the fifth international conference on Autonomous Agents, Montreal, Canada, ACM Press, pp. 116-117, 2001.

[Banavar 2000] Banavar, G., Beck, J., Gluzberg, E., Munson, J., Sussman, J., Zukowsli, D., "Challenges: An Application Model for Pervasive Computing", Proceedings 6th Annual Intl. Conference on Mobile Computing and Networking (MobiCom 2000), August 2000, pp.266-274.

[Baumann 2000] Baumann, J. "Mobile agents: control algorithms", LNCS 1658, Springer, 2000.

[Brebner 2002] Brebner, G., Durand, Y., Perret, S. Position Paper - A Middleware Architecture for Personalized Communities of Devices, The Fourth International Conference on Distributed Communities on the Web, 3-5 April 2002, Sydney, Australia

[Cardelli 2000] L. Cardelli, A. Gordon " Mobile Ambients", TCS Special issue on coordination D.L Metayer editor TCSB Vol 241/1 July 2000.

[Cheverst 2000] K. Cheverst, N. Davies, K. Mitchell, A. Friday, Experiences of Developing and Deploing a Context-Aware Tourist Guide: The GUIDE project. Proc of MOBICOM'2000, Boston 2000, pp.20-31.

[Cuce 2002] Cuce S., Zaslavsky A., "Supporting Multiple Consistency Models for a Mobility Enabled File System using a Component Based Framework", Accepted for publication in a Special Issue of ACM Mobile Networks and Applications (MONET), 2002.

[Deitel 2002] H.M.Deitel, P.J.Deitel, T.R.Nieto, K.Steinbuhler, "Wireless Internet & Mobile Buisness. How to Program", Prentice Hall, 2002.

[Efstratiou 2001] C. Efstratiou, K. Cheverst, N. Davies, A. Friday, An Architecture for the Effective Support of Adaptive Context-Aware Applications, in Proc. of 2nd International Conference on Mobile Data Management, Hong-Kong, January 2001. Lecture Notes in Computer Science, Vol# 1987.

[Gray 2000] R. Gray and G. Cybenko and D. Kotz and D. Rus. Mobile Agents: Motivations and State of the Art. Handbook of Agent Technology. J. Bradshaw (ed.), 2000, MIT Press.

[Hart 2001] D. Hart, M. Tudoreanu, E. Kraemer, Mobile agents for monitoring distributed systems, Proceedings of the fifth international conference on Autonomous Agents, Montreal, Canada, ACM Press, pp. 232-233, 2001.

[Harter 1999] Harter, A. Hopper, A., Steggles, P., Ward, A., Webster, P., "The Anatomy of a Context-Aware Application", Proceedings 5th Annual Intl. Conference on Mobile Computing and Networking (MobiCom'99), August 1999, pp.59-68.

[Indulska 2001] Indulska, J., Loke, S.W., Rakotonirainy, A., Witana, V., Zaslavsky, A. "An Open Architecture for Pervasive Systems", 3d IFIP WG 6.1 International Working Conference on Distributed Applications and Interoperable Systems (DAIS'2001),Krakow,September 2001. Published by Kluwer

[Jun 2000] K. Jun, L. Bölöni, K. Palacz and D. C. Marinescu, "Agent-Based Resource Discovery", Proceedings of the 9th Heterogeneous Computing Workshop, Cancun, Mexico, May 2000, IEEE

[Kindberg 2002] T. Kindberg and J. Barton, "A web-based nomadic computing system", Cooltown Project, HP Research Labs, http://www.cooltown.com/dev/wpapers/nomadic/

[Klusch 2001] M. Klusch. Information Agent Technology for the Internet: A Survey. Journal on Data and Knowledge Engineering, Special Issue on Intelligent Information Integration. D. Fensel (Ed.), Vol. 36(3), Elsevier Science.

[Loke 2000] Loke, S.W., Rakotonirainy, A., and Zaslavsky, A. Enabling Awareness in Dynamic Mobile Agent Environments. Proceedings of the 15th Symposium on Applied Computing (SAC 2000), Como, Italy, March 2000, ACM Press.

[Loke 2001a] Loke S.W., Zaslavsky A., Yap B., Fonseka J., An Itinerary Scripting Language for Mobile Agents in Enterprise Applications, 2nd Asia-Pacific Conference on Intelligent Agent Technology (IAT-2001), Maebashi TERRSA, Maebashi City, Japan October 23-26, 2001

[Loke 2001b] Loke S.W., Rakotonirainy A., Zaslavsky A. "An enterprise viewpoint of wireless virtual communities and the associated uses of software agents", In: Internet Commerce and Software Agents, S.M.Rahman, R.Bignall (Eds), Idea Group Publishing, pp.265-287, 2001.

[Loke 2001c] S.W. Loke. An Overview of Mobile Agent Technology for Distributed Applications: Possibilities for Future Enterprise Systems. To appear in the Informatica Journal, 2001.

[Loke 2002] Loke S.W., Zaslavsky A. "Mobile agent supported cooperative work: the ITAG scripting language approach", Accepted as a chapter in Y.Ye and E. Churchill (Eds) "Agent supported collaborative work", Kluwer Academic publishers, 2002

[Mobility 1999] "Mobility: processes, computers and agents", (Eds) D.Milojicic, F.Douglis, R.Wheeler, ACM Press, 1999

[Moro 2000] Moro, G., Viroli, M. "On observing and constraining active systems", A.Omicini, R. Tolksdorf, F.Zambonelli (Eds): Engineering Societies in the Agent World, ESAW'2000, LNAI 1972, pp.34-50, 2000.

[Noble 1997] Noble, B., Satyanarayanan, M., Narayanan, D. Filton J.E, Flinn J.,Walker K. , ``Agile Application Aware Adaptation for Mobility" 16th ACM Symposium on Operating System Principles 1997

[Nzama 2001] Nzama M., Ng A., and Zaslavsky A. "Adaptive Delivery of Multimedia Data in Heterogeneous and Mobile Environments", International Conference On Mobile Data Management (MDM '2001) LNCS Vol.1987, pp.41-52, 2001.

[Papastavrou 1999] S. Papastavrou, G. Samaras and E. Pitoura, Mobile Agents for World Wide Web Distributed Database Access. IEEE Transactions on Knowledge and Data Engineering, 12(5), pp 802-820, 2000

[Rasheed 1997] Rasheed, A. Zaslavsky, A., "A Transaction Model to Support Disconnected Operation in a Mobile Computing Environment", 4th International Conference on Object-Oriented Information Systems, OOIS'97, Brisbane, November, 1997.

[Spriestersbach 2001] A. Spriestersbach, H. Vogler, F. Lehmann, T. Ziegert, "Integrating Context Information into Enterprise Applications for the Mobile Workforce -A Case Study", Workshop on Mobile Commerce, MobiComp'01, Rome, 2001, pp.55-59.

[Stanski 1998] P. Stanski and A. Zaslavsky, 1998, "Expressing Dynamics of Mobile Agent Systems Using Ambient Calculus",.9th International Workshop on Database and Expert Systems Applications, August 26-28, 1998, Vienna, Austria, IEEE Computer Press, pp.434-439.

[Suryanarayana 2001] Suryanarayana L., Hjelm J. "CC/PP for content negotiation and contextualization", International Conference On Mobile Data Management (MDM '2001) LNCS Vol.1987, pp.239-245, 2001.

[Zaslavsky 1998a] Zaslavsky, A. and Tari, Z. "Mobile computing: Overview and current status", Australian Computer Journal, Special Issue on Mobile Computing, Vol.30, No.2, pp.42-52, 1998

[Zaslavsky 2002a] Zaslavsky A "Adaptability and Interfaces: Key to Efficient Pervasive Computing", NSF Workshop series on Context-Aware Mobile Database Management, Brown University, Providence, 24-25 January, 2002

[Zaslavsky 2002b] A. Zaslavsky, "Mobility in enterprise applications", Keynote at 5th International Conference on Business Information Systems, W.Abramowicz (Ed), Poland, 24-25 April, 2002.