Middleware-based Development of Context-aware Applications with Reusable Components

Ph.D. Thesis Defense

Wednesday, September 30th 2009

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Presentation outline

- Introduction
- Foundations
- Development methodology
- Pluggable and modular middleware architecture
- Evaluation
- Conclusions and future work

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What is context-awareness?

- Post-desktop era: the vision of **Ubiquitous computing** [WEISER 1991, WEISER 1993]
- "[context is] the **location** of use, nearby **people**, **hosts** and accessible **devices** as well as changes to these things over time" [SCHILIT 1994]
- "[context is] any information that can be used to characterize the situation of an entity; [where] an entity is a **person**, **place**, or **object** that is considered relevant to the interaction between a user and an application, including the **user** and the **application** themselves" [DEY 2001]
- Context-awareness: "The ability of a system to **sense** the context in run-time and **use it**"

WEISER, M. "The computer for the 21st century", *Scientific American* (Feb. 1991).
WEISER, M. "Hot topics: ubiquitous computing", *Computer 26, 10* (Oct. 1993), 71–72.
SCHILIT, B. N., ADAMS, N., WANT, R. "Context-aware computing applications", IEEE Workshop on Mobile Computing Systems and Applications (WMCSA'94), Santa Cruz, CA, USA, IEEE Computer Society (1994) p. 89-101
DEY, A. K., "Understanding and using context", Personal and Ubiquitous Computing, Vol. 5, 1 (2001) p. 4–7

Motivation: context use in applications

Context-aware profile manager for smart-phones

Personalized exercise monitoring

Context-aware augmented reality

Google Latitude

Context-aware media player

Signal-strength predictor

PRM Travel assistant

Motivation: potential of context use

- Strong mobile phone penetration
  - 61% of the world population (more than 4.1 billion people) [ITU 2009]
- Proliferation of embedded computing
  - Home and office appliances, modern aircrafts, cars, etc [WRIGHT 2009]
- Realizing the vision of ubiquitous computing
  - The Singapore and Korea examples [BELL 2007]

ITU. "Measuring the Information Society: The ICT Development Index", *International Telecommunication Union*, 2009.
CHARETTE, R.N., "This Car Runs on Code," IEEE Spectrum (Feb. 2009)
WRIGHT, A., "Making sense of sensors," Communications of the ACM, vol. 52, 2, 2009, pp. 14-15.
BELL, G., DOURISH, P., "Yesterday's tomorrows: notes on ubiquitous computing's dominant vision," Personal Ubiquitous Computing, vol. 11, 2007, pp. 133-143.

Challenges

What are the *software engineering challenges* faced by the developers of such systems?

- **Software complexity**
  - Common challenge [HORN 2001]
  - Context-aware behavior renders the underlying code significantly more complex
- **Heterogeneity and Interoperability**
  - Mobile and ubiquitous computing → diverse ecosystem
  - Sharing data (e.g., context information) and coordinating their actions
- **Resource limitations**
  - Evolving beyond the desktop model → resource constraints (battery, memory, CPU, display size, etc)
- **Modularity**
  - Diverse mobile & embedded device ecosystem → modular solutions

HORN, P. "Autonomic computing: IBM's perspective on the state of information technology", 2001.

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Challenges in the literature

- "... ***lack of supporting infrastructure for*** *capturing and processing context* ..." [PASCOE 1997]
- "... *context is handled in an* ***improvised manner***" [DEY 2001]
- "... ***high application development overheads, social barriers*** *associated with privacy and usability, and an* ***imperfect understanding*** *of* [context use]" [HENRICKSEN 2006]
- *"...what is missing, however, has been* ***the middleware*** *that will enable the applications to juxtapose information about your physical location with data from other applications."* [WRIGHT 2009]

PASCOE, J. "The stick-e note architecture: extending the interface beyond the user", *2nd International Conference on Intelligent User Interfaces* (Orlando, Florida, USA, 1997), ACM, pp. 261–264.

DEY, A. K., ABOWD, G. D., AND SALBER, D. "A conceptual framework and a toolkit for supporting the rapid prototyping of context-aware applications", *Human-Computer Interaction 16*, 2 (2001), 97–166.

HENRICKSEN, K., AND INDULSKA, J. "Developing context-aware pervasive computing applications: models and approach", *Pervasive and Mobile Computing 2*, 1 (Feb. 2006), 37–64.

WRIGHT, A. "Get smart", *Communications of the ACM 52*, 1 (Jan. 2009), 15–16.

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Thesis statement

Traditional approaches for developing software applications are **insufficient for meeting the software engineering challenges** faced by the developers of context-aware systems, targeting mobile and ubiquitous computing environments.

Appropriate **software, methods and tools** are needed to render the development of context-aware applications **easier, faster and more cost-efficient**.

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Approach

- Development methodology
  - Separation-of-concerns
  - Software reuse
  - Context model and query language
  - Model-driven development approach
- Middleware architecture
  - Open/Pluggable
  - Modular
  - Autonomic resource management

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Basic concepts

- Context
  - Any information affecting the interaction between a user and an application [DEY 2000, DEY 2001]
- Adaptation
  - A process by which software changes its behavior in order to better match the changing environment [McKINLEY 2004]
    - Parameter-based adaptation
    - Compositional adaptation
- Variants
  - An application variant is any parameter-based or compositional-based configuration of the application, maintaining its original functional properties

McKINLEY, P. K., SADJADI, S. M., KASTEN, E. P., AND CHENG, B. H. C. "Composing adaptive software", *IEEE Computer 37*, 7 (2004), 56–64.

Basic concepts

- Self-adaptive, context-aware behavior
  - The ability of a system to *sense* its environment and react accordingly in order to *shape* it, aiming for a predefined goal
- Perceived utility
  - A function U_p that for any context point c_i it maps any two variants v_x and v_y to scalar values (e.g., in the range [0, 1]) so that $U_p(c_i, v_x) > U_p(c_i, v_y)$ if and only if the user prefers v_x to v_y from her or his point of perception
  - Based on a perceived utility function U_p, the set of available variants can be totally ordered (v_{i1}, v_{i2}, ..., v_{iN}) and thus enable self-adaptive, context-aware behavior where the selected variant is chosen using U_p

PASPALLIS, N., KAKOUSIS, K., PAPADOPOULOS, G. A., "A multi-dimensional model enabling autonomic reasoning for context-aware pervasive applications", Workshop for Human Control of Ubiquitous Systems (HUCUBIS 2008) in conjunction with the 5th Annual International Conference on Mobile and Ubiquitous Systems: Computing, Networking and Services (Mobiquitous), Trinity College Dublin, Ireland, July 21-25, 2008, ACM Press

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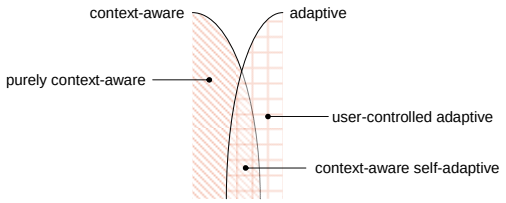
Classification of context-aware applications



- Context-aware
  - Use context information in run-time
- Adaptive
  - Are able to adjust their behavior (e.g., through parameter or compositional-based adaptation) in run-time
- Context-aware, self-adaptive
  - Use context information in order to autonomously adapt their behavior at run-time

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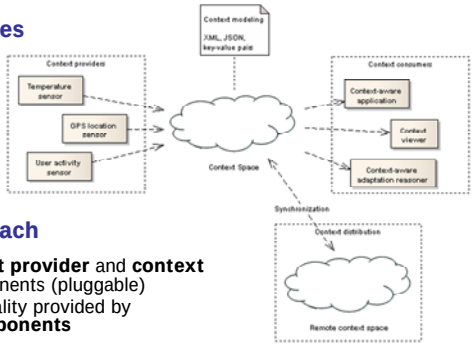
High-level view of context management

Required features

- Acquisition
- Storage
- Access
- Distribution

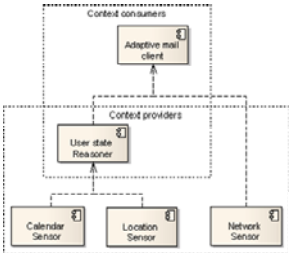


Proposed approach

- Individual **context provider** and **context consumer** components (pluggable)
- Common functionality provided by **specialized components**
  - Replaceable
  - Optional

Separation of concerns: context providers & consumers

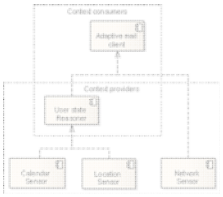
- Context **provider** and context **consumer** roles
- Plug-ins
  - **Sensors** have no context dependencies
    - Pure context providers
      - Location sensor
      - Network sensor
      - Calendar sensor
  - **Reasoners** have context dependencies
    - Act as context providers and as context consumers at the same time
      - User status reasoner
  - **Context clients**
    - Pure context consumers
      - Adaptive mail client

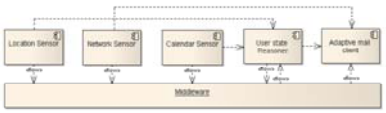


Separation of concerns: context providers & consumers

- Why middleware?
  - Coordinated life-cycle control
  - Centralization of commonly used functionality
  - Can facilitate interoperability
  - Support for multiple concurrent applications
  - Support for multiple context providers

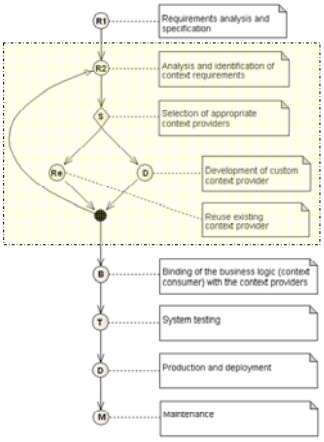
Logical bindings





Development methodology

- Identify the required context types
  - E.g., "User state"
- Select an appropriate provider
  - 1. Reuse an existing provider
  - 2. Develop a custom one
- If needed, update the context requirements
  - E.g., if the selected plug-in has additional context dependencies (e.g., "Location" and "Calendar")
- Repeat until all context requirements are resolved



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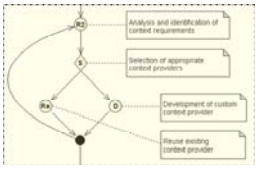
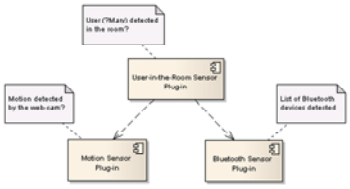
Example: Context-aware Media Player (CaMP)

- Motion sensor plug-in
- Bluetooth sensor plug-in
- User-in-the-room sensor plug-in





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Developing context plug-ins

Programmatic development

- Define metadata
  - Provided context types
  - Needed context types (optional)
- Realize the internal mechanism
  - Respond to input context events
  - Wrap an underlying hardware sensor
  - Explicitly poll data (e.g., memory sensor)
- Package
  - Create the reusable component

Model-driven development (MDD)

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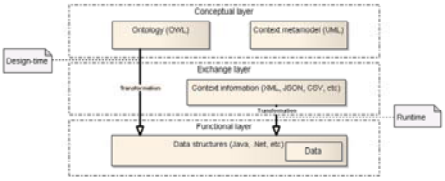
Context model

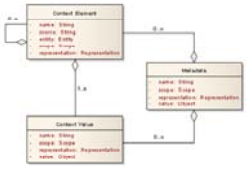
- Layered context model
  - Conceptual layer
  - Exchange layer
  - Functional layer



WAGNER, M., REICHLE, R., KHAN, M. U., GEIHS, K., LORENZO, J., VALLA, M., FRA, C., PASPALLIS, N., PAPADOPOULOS, G. A., "A Comprehensive Context Modeling Framework for Pervasive Computing Systems", 8th IFIP International Conference on Distributed Applications and Interoperable Systems (DAIS), 4-6 June, 2008, Oslo, Norway, Springer Verlag LNCS 5053, pp. 281-295

Context ontology and context metamodel

- Context ontology
  - Design-time
    - Semantic consistency
    - Automatic generation of code using MDD
      - Data structures, Serialization/de-serialization code, IRO templates
  - Run-time
    - Relation inferring
    - Inter-representation transformation (IRO)
- Context metamodel
  - Context elements
  - Context values
  - Metadata



Context access

- Two main methods for accessing context
  - Simple queries
    - Access latest value (or values) of context type X
      - E.g., what is the latest recorded location?
    - Subscribe for notification of context type Y changes
      - E.g., notify whenever a change occurs in the set of nearby Bluetooth devices
  - Context query language
    - Access latest value(s) of context type X under condition C
      - E.g., what are the temperature recordings in the last 1 hour?
    - Subscribe for notification of context type Y when condition C is satisfied
      - E.g., notify me whenever my location is within 1000m of location <lon, lat>

REICHLE, R., WAGNER, M., KHAN, M. U., GEIHS, K., VALLA, M., FRA, C., PASPALLIS, N., PAPADOPOULOS, G. A., "A Context Query Language for Pervasive Computing Environments", *5th IEEE Workshop on Context Modeling and Reasoning (CoMoRea)in conjunction with the 6th IEEE International Conference on Pervasive Computing and Communication (PerCom)*, Hong Kong, 17–21 March 2008, IEEE Computer Society Press, pp. 434-440

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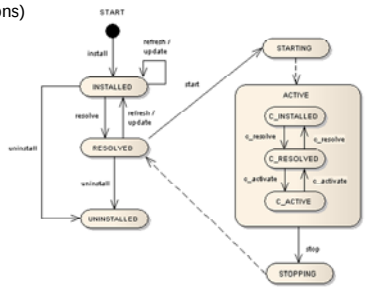
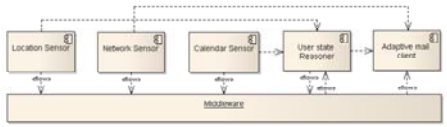
Component-based middleware

- Middleware components
  - Core components
  - Context providers (plug-ins)
  - Context consumers (applications)
- Based on OSGi
  - Application lifecycle
    - **INSTALLED**
      RESOLVED
      ACTIVE
  - Extended OSGi component lifecycle
    - **C_INSTALLED**
    - **C_RESOLVED**
    - **C_ACTIVE**



Dynamic resolution and activation

- The middleware monitors
  - Required context types (i.e., from context-aware applications, context reasoner plug-ins and other middleware components)
  - Provided context types (i.e., as reported by the installed/available plug-ins)
- Resolution mechanism
  - Identify resolved context plug-ins
- Activation mechanism
  - Selects plug-ins for activation



Experimental evaluation: method

- Predefined multi-step scenario using a PDA
  - Varying context needs
- Combined set of real and simulated plug-ins
  - Real: *Bluetooth*, *WiFi*, *GSM*, and *GPS* sensors
  - Simulated: *RFID*, *Light*, and *Weather* sensors
- Measure resource consumption
  - Battery use
  - Memory use
- Repeat measurements
  - Autonomic activation
  - All active

PASPALLIS, N., ROUVOY, R., BARONE, P., PAPADOPOULOS, G. A., ELIASSEN, F., MAMELLI, A., "A Pluggable and Reconfigurable Architecture for a Context-aware Enabling Middleware System", *10th International Symposium on Distributed Objects, Middleware, and Applications (DOA'08)*, Monterrey, Mexico, Nov 10 - 12, 2008, Springer Verlag LNCS 5331, pp. 553-570

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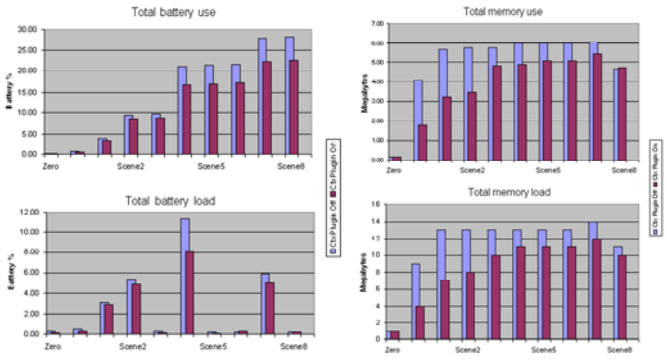
Experimental evaluation: results



Memory utilization: +21.29%

Battery utilization: +20.95%

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Modular architecture: core services

- Provided services
  - Context access
  - Context management
  - Context simulation
- Required services
  - Context repository
  - Context query
  - Context model

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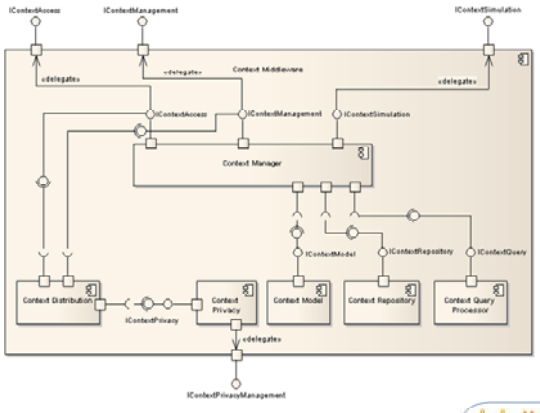
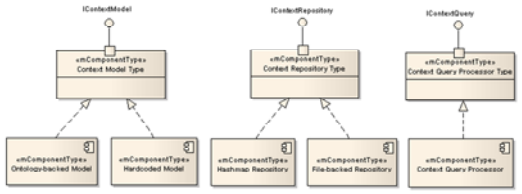
Modular architecture: high-level architecture



Modular architecture: variability

- Adding/removing optional components
  - Context distribution
  - Context query processor
- Substituting components
  - Hardcoded model for simple applications
  - Hashmap-based versus DBMS-based context repository



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Evaluation approach

- Quantitative analysis
  - Case study-based evaluation
    - Context-aware Media Player (CaMP)
    - Signal Strength Predictor (SSP)
  - MUSIC pilot applications (indirect use)
    - PRM Travel Assistant
    - SatMotion
  - Other plug-in developers
    - NTNU (MS thesis: InstantSocial), Telefonica, Integrasys and HP
  - EPL-429 course applications
    - Training, using, evaluating
    - Feedback collected via surveys
- Qualitative analysis
  - Requirement-driven

Quantitative evaluation

EP-429-based evaluation

- Design a context-aware application
  - Business logic
  - Context-aware logic (required context types)
- Realize the appropriate plug-ins
  - Implement from scratch
  - Reuse existing plug-ins
- Integrate the application
  - Implement the business logic
  - Bind with the context middleware

Quantitative evaluation

Results

- Almost all would prefer the proposed methodology to the ad-hoc one
  - 11 out of 12
- Most tasks were of low-to-medium complexity
  - Most complex task: context modeling (medium-to-high complexity)
- Smooth learning curve
  - ~23 hours for preparation and ~20 hours for implementation
- Similar results reported by MUSIC developers

Qualitative analysis: Requirements-driven

Functional

- Application specific context acquisition, analysis and detection
- Context-triggered action
- Heterogeneity
- Uncertainty
- Context histories
- Inference of inter-dependencies
- Multiple concurrent applications
- Transparent distribution
- Privacy
- Traceability and control
- Interoperability and standards

Extra-functional

- Ease of building
- Modularity
- Separation of concerns
- Code reuse
- Uniform development support
- Evolution
- Scalability
- Dynamic behavior
- Platform independence
- Lightweight architecture
- Adoption of existing patterns and standards
- Support for mobility
- Fault-tolerance
- Ease of deployment and configuration
- Resource efficiency

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Main contributions

- Development methodology
  - Separation-of-concerns
  - Code reuse
  - Context model and query language
  - Model-driven development approach
- Middleware architecture
  - Open/Pluggable
  - Modular
  - Autonomic activation with resource optimization

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Future work

- Complete context-aware, self-adaptive applications with reusable components [PASPALLIS 2009]
  - Application components annotated with metadata characterizing its extra-functional (i.e., self-adaptive) properties
  - Specialized algorithms used to evaluate the available components in run-time
- Learning from user feedback [KAKOUSIS 2008]
  - Ubiquitous computing → getting the user out of the loop
  - Minimal, non-intrusive user feedback → train the autonomic (context-aware, self-adaptive behavior) behavior of the application

PASPALLIS, N., ELIASSEN, F., HALLSTEINSEN, F., AND PAPADOPOULOS, G. A., "Developing Self-Adaptive Mobile Applications and Services with Separation-of-Concerns", At Your Service: Service-Oriented Computing from an EU Perspective, E. Di Nitto, A-M. Sassen, O. Traverso and A. Zwegers (eds), MIT Press, June 2009, chapter 6, pp. 129-158

KAKOUSIS, K., PASPALLIS, N., AND PAPADOPOULOS, G. A., "Optimizing the Utility Function-based Self-adaptive Behavior of Context-aware Systems using User Feedback",10th International Symposium on Distributed Objects, Middleware, and Applications (DOA'08), Monterrey, Mexico, Nov 10 - 12, 2008, Springer Verlag LNCS 5331, pp. 657-674

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- European Commission

Questions?

Thank you!

Publications: Thesis-specific

- **PASPALLIS, N.**, ELIASSEN, F., HALLSTEINSEN, S., AND PAPADOPOULOS, G. A., **"Developing self-adaptive mobile applications and services with separation-of-concerns"**, *At Your Service: Service-Oriented Computing from an EU Perspective*, E. Di Nitto, A-M. Sassen, O. Traverso and A. Zwegers (eds), MIT Press, June 2009, chapter 6, pp. 129-158
- GEIHS, K., BARONE, P., ELIASSEN, F., FLOCH, J., FRICKE, R., GJORVEN, E., HALLSTEINSEN, S., HORN, G., KHAN, M. U., MAMELLI, A., PAPADOPOULOS, G. A., **PASPALLIS, N.**, REICHLE, R., STAV, E., **"A comprehensive solution for application-level adaptation"**, *Software – Practice and Experience Journal*, Online ISSN: 1097-024X, Print ISSN: 0038-0644, Copyright 2008 John Wiley & Sons, Ltd., Published Online: Sep 15 2008, DOI: 10.1002/spe.900
- **PASPALLIS, N.**, ROUVOY, R., BARONE, P., PAPADOPOULOS, G. A., ELIASSEN, F., MAMELLI, A., **"A pluggable and reconfigurable architecture for a context-aware enabling middleware system"**, *10th International Symposium on Distributed Objects, Middleware, and Applications (DOA'08)*, Monterrey, Mexico, Nov 10 - 12, 2008, Springer Verlag LNCS 5331, pp. 553-570
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Publications: Thesis-specific

- WAGNER, M., REICHLE, R., KHAN, M. U., GEIHS, K., LORENZO, J., VALLA, M., FRA, C., **PASPALLIS, N.**, PAPADOPOULOS, G. A., **"A comprehensive context modeling framework for pervasive computing systems**, *8th IFIP International Conference on Distributed Applications and Interoperable Systems (DAIS)*, Oslo, Norway, 4-6 June, 2008, Springer Verlag LNCS 5053, pp. 281-295
- REICHLE, R., WAGNER, M., KHAN, M. U., GEIHS, K., VALLA, M., FRA, C., **PASPALLIS, N.**, PAPADOPOULOS, G. A., **"A context query language for pervasive computing environments**, *5th IEEE Workshop on Context Modeling and Reasoning (CoMoRea)in conjunction with the 6th IEEE International Conference on Pervasive Computing and Communication (PerCom)*, Hong Kong, 17–21 March 2008, IEEE Computer Society Press, pp. 434-440
- **PASPALLIS, N.**, PAPADOPOULOS, G. A., **"An Approach for Developing Adaptive, Mobile Applications with Separation of Concerns**, *30th Annual International Computer Software and Applications Conference (COMPSAC)*, Chicago, IL, USA, September 17-21, 2006, IEEE Computer Society Press, pp. 299-306

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- KAKOUSIS, K., **PASPALLIS, N.**, PAPADOPOULOS, G. A., **"Optimizing the utility function-based self-adaptive behavior of context-aware systems using user feedback"**, *10th International Symposium on Distributed Objects, Middleware, and Applications (DOA'08)*, Monterrey, Mexico, Nov 10 - 12, 2008, Springer Verlag LNCS 5331, pp. 657-674
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