

*Commenced Publication in 1973*

Founding and Former Series Editors:

Gerhard Goos, Juris Hartmanis, and Jan van Leeuwen

## Editorial Board

David Hutchison

*Lancaster University, UK*

Takeo Kanade

*Carnegie Mellon University, Pittsburgh, PA, USA*

Josef Kittler

*University of Surrey, Guildford, UK*

Jon M. Kleinberg

*Cornell University, Ithaca, NY, USA*

Friedemann Mattern

*ETH Zurich, Switzerland*

John C. Mitchell

*Stanford University, CA, USA*

Moni Naor

*Weizmann Institute of Science, Rehovot, Israel*

Oscar Nierstrasz

*University of Bern, Switzerland*

C. Pandu Rangan

*Indian Institute of Technology, Madras, India*

Bernhard Steffen

*University of Dortmund, Germany*

Madhu Sudan

*Massachusetts Institute of Technology, MA, USA*

Demetri Terzopoulos

*New York University, NY, USA*

Doug Tygar

*University of California, Berkeley, CA, USA*

Moshe Y. Vardi

*Rice University, Houston, TX, USA*

Gerhard Weikum

*Max-Planck Institute of Computer Science, Saarbruecken, Germany*

Bruno Bouyssounouse Joseph Sifakis (Eds.)

# Embedded Systems Design

The ARTIST Roadmap  
for Research and Development

## Volume Editors

Bruno Bouyssounouse

ARTIST Technical Coordinator

Joseph Sifakis

ARTIST Scientific Coordinator

Verimag Laboratory

Centre Equation, 2 avenue de Vignate, 38610 Gieres, France

E-mail: {Bruno.Bouyssounouse,Joseph.Sifakis}@imag.fr

Library of Congress Control Number: 2005921510

CR Subject Classification (1998): C.3, C.2, D.2, D.3, D.4, K.6

ISSN 0302-9743

ISBN 3-540-25107-3 Springer Berlin Heidelberg New York

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, re-use of illustrations, recitation, broadcasting, reproduction on microfilms or in any other way, and storage in data banks. Duplication of this publication or parts thereof is permitted only under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer. Violations are liable to prosecution under the German Copyright Law.

Springer is a part of Springer Science+Business Media

[springeronline.com](http://springeronline.com)

© Springer-Verlag Berlin Heidelberg 2005

Printed in Germany

Typesetting: Camera-ready by author, data conversion by Markus Richter, Heidelberg

Printed on acid-free paper      SPIN: 11400707      06/3142      5 4 3 2 1 0

# Preface

Embedded systems now include a very large proportion of the advanced products designed in the world, spanning transport (avionics, space, automotive, trains), electrical and electronic appliances (cameras, toys, televisions, home appliances, audio systems, and cellular phones), process control (energy production and distribution, factory automation and optimization), telecommunications (satellites, mobile phones and telecom networks), and security (e-commerce, smart cards), etc. The extensive and increasing use of embedded systems and their integration in everyday products marks a significant evolution in information science and technology. We expect that within a short timeframe embedded systems will be a part of nearly all equipment designed or manufactured in Europe, the USA, and Asia.

There is now a strategic shift in emphasis for embedded systems designers: from simply achieving feasibility, to achieving optimality. Optimal design of embedded systems means targeting a given market segment at the lowest cost and delivery time possible. Optimality implies seamless integration with the physical and electronic environment while respecting real-world constraints such as hard deadlines, reliability, availability, robustness, power consumption, and cost. In our view, optimality can only be achieved through the emergence of embedded systems as a discipline in its own right.

Embedded systems are of strategic importance in modern economies. They are used in mass-market products and services, where value is created by supplying either functionality or quality. Europe currently has a strong position in sectors where embedded technologies play a central role. It has a lead in civil avionics where fly-by-wire technology provides an overwhelming competitive advantage in the cost of operating aircraft. Europe is also well positioned in the space sector, specifically for launch vehicles and satellites. In the automotive industry, European manufacturers and their suppliers enjoy a leading technological advantage for engine control, and emerging technologies such as brake-by-wire and drive-by-wire. Railway signalling in Europe relies on embedded systems, and allows faster, safer, and heavier traffic. Embedded applications will be extensively used to make energy distribution more flexible, especially in view of the coming market liberalization. Embedded technologies are strategic for the European telecommunications sector. Finally, Europe is also well positioned for e-services (e-banking, e-health, e-training), based on the leading edge in smart-card related technologies.

Embedded systems design raises challenging problems for research, including:

- Security  
Economic, citizenship, and societal activities in Europe rely increasingly on embedded applications. Widespread acceptance and reliance on these will depend on the availability of seamless solutions for securing rights and privacy.
- Reliable, mobile, embedded services  
Electronic commerce and e-services in a wireless world will need provably correct foundations to ensure further growth.

- Large-scale heterogeneous distributed systems  
Applications such as automated highways, advanced air traffic control, or next-generation factory automation require full-scale, industry-ready paradigms, methodologies, and advanced prototypes. These need to integrate heterogeneous elements from different, perhaps competing providers, in evolving embedded environments.
- Adaptive embedded systems  
Tomorrow's resource-constrained applications, such as image processing, telecommunications, and industrial automation, are expected to see drastic advances in performance and dependability, with the ability to adapt to dynamic changes in resource needs, including power/energy, bandwidth, memory, and computing power.
- Component-based design, validation, and tool-based certification  
Development costs and time-to-market could be vastly reduced, by enabling the incremental design and formal validation of arbitrarily complex systems.

This roadmap was written by the IST-2001-34820 ARTIST FP5 Accompanying Measure on Advanced Real-Time Systems, funded by the European Commission, and which started April 1st, 2002 and ended March 31st 2005.

The ARTIST FP5 workplan includes, in addition to providing this roadmap, advancing the state of the art and structuring research on embedded systems in Europe. It gathered together 28 leading European research institutions, as well as many top researchers in the area.

The aim of ARTIST FP5 was to coordinate the R&D effort in the area, to improve awareness of academics and industry, especially about existing innovative results and technologies, standards, and regulations, and to define innovative and relevant work directions, identify obstacles to scientific and technological progress, and propose adequate strategies for circumventing them.

ARTIST FP5 was implemented as a set of four coordinated actions, each centred on a high-priority thematic area of research on embedded systems. Correspondingly, the roadmap is organised into four parts.

Action 1: Hard Real Time. This action was led by Professor Albert Benveniste of INRIA (France), and focused on aspects of hard real-time applications, bringing together competencies from synchronous languages, time-triggered systems, and schedulers.

Action 2: Component-Based Design and Development. This action was led by Professor Bengt Jonsson of Uppsala University (Sweden), and focused on both theoretical and practical aspects of modelling complex systems with emphasis on methods (compositionality, composability) and standards (e.g. UML).

Action 3: Adaptive Real-Time Systems for QoS Management. This action was led by Professor Giorgio Buttazzo of the University of Pavia (Italy), and focused on soft real-time approaches and technology for telecommunications, large open systems, and networks. It gathered together teams with expertise in real-time operating systems and middleware.

Action 4: Execution Platforms. This action was led by Professor Lothar Thiele of the Swiss Federal Institute of Technology (ETHZ), and focused on issues at the frontier between hardware and software – and their implications for embedded systems design.

To enhance readability, each of the four parts of the roadmap follows a similar structure, although there are domain-related specificities. Also, inevitably, some topics may be treated in more than one part of the document, but the index should help the reader find the different relevant texts for a given topic.

Oversight for ARTIST FP5 was provided by the Artist Industrial Advisory Board (IAB), which reviewed the roadmap. The ARTIST IAB is chaired by Dr. Dominique Potier, Scientific Director for Software Technologies, Thalès.

We would like to thank all the contributors to the roadmap, including the engineers and researchers who participated in the various technical meetings and workshops, as well as the industrial leaders who granted interviews and/or provided information in the questionnaire. Special thanks also go to the Artist FP5 reviewers and the project officer, for constructive and stimulating comments.

The elaboration of this roadmap provided the opportunity for fertile interaction between key players in the area of embedded systems, and proved to be useful for structuring the area.

The work and the strategic orientations and conclusions of ARTIST FP5 led to the creation of the ARTIST2 FP6 Network of Excellence on Embedded Systems Design. Information about ARTIST2 is available on the web-site: <http://www.artist-embedded.org/FP6>.

This roadmap usefully complements other existing roadmapping work from ITEA and MEDEA+. We hope that it will be useful for both research and industry and that it will serve to advance awareness about the state of the art and provide insights on possible avenues for R&D.

Grenoble, January 2005

Bruno Bouyssounouse  
*ARTIST Technical Coordinator*  
*Verimag Laboratory, France*

Joseph Sifakis  
*ARTIST Scientific Coordinator*  
*Verimag Laboratory, France*

# Editors

Bruno Bouyssounouse  
*ARTIST Technical Coordinator*  
Joseph Sifakis  
*ARTIST Scientific Coordinator*

Verimag Laboratory, France

Verimag Laboratory, France

# Contributors

## Part I: Hard Real-Time Development Environments

Coordinator: Albert Benveniste     INRIA, France

Jos Baeten	Eindhoven Technical University, The Netherlands
Philippe Baufreton	Hispano-Suiza, France
Albert Benveniste	INRIA, France
Samuel Boutin	Renault, France
Bruno Bouyssounouse	Verimag Laboratory, France
Dominique Brière	Airbus, France
Paul Caspi	Verimag Laboratory, France
Werner Damm	OFFIS, Germany
Emmerich Fuchs	Vienna Technical University, Austria
Vered Gafni	Israel Aircraft Industries, Israel
Thierry Gautier	INRIA, France
Drora Goshen	Israel Aircraft Industries, Israel
Guenther Gruensteidl	Alcatel, Austria
Nicolas Halbwachs	Verimag Laboratory, France
Hermann Kopetz	Vienna Technical University, Austria
Kim Larsen	Aalborg University, Denmark
Hervé Le Berre	Airbus, France
Rainer Leupers	RWTH Aachen, Germany
Brian Nielsen	Aalborg University, Denmark
Ernst-Rüdiger Olderog	OFFIS, Germany
Yiannis Papadopoulos	University of York, UK
Philipp Peti	Vienna Technical University, Austria
Manfred Pisecky	TTTech, France
Peter Puschner	Vienna Technical University, Austria
Jörn Rennhack	Airbus, Germany
Alberto Sangiovanni-Vincentelli	PARADES, Italy
Christian Scheidler	DaimlerChrysler, Germany
Arne Skou	Aalborg University, Denmark
Yves Sorel	INRIA, France
Ulrich Virnich	Siemens, Germany
Birgit Vogel-Heuser	University of Wuppertal, Germany
Reinhard Wilhelm	Saarland University, Germany
Tim Willemse	Eindhoven Technical University, The Netherlands

## Part II: Component-Based Design and Integration Platforms

Coordinator: Bengt Jonsson

University of Uppsala, Sweden

Ed Brinksma	University of Twente, The Netherlands
Geoff Coulson	Lancaster University, UK
Ivica Crnkovic	Mälardalen University, Sweden
Andy Evans	University of York, UK
Sébastien Gérard	CEA, France
Susanne Graf	Verimag Laboratory, France
Holger Hermanns	Saarland University, Germany
Jean-Marc Jézéquel	INRIA, France
Bengt Jonsson	University of Uppsala, Sweden
Noël Plouzeau	INRIA, France
Anders Ravn	Aalborg University, Denmark
Philippe Schnoebelen	LSV Laboratory, France
Francois Terrier	CEA, France
Angelika Votintseva	OFFIS, Germany

## Part III: Adaptive Real-Time Systems for Quality of Service Management

Coordinator: Giorgio Buttazzo

University of Pavia, Italy

Luis Almeida	University of Aveiro, Portugal
Alejandro Alonso	Technical University of Madrid, Spain
Guillem Bernat	University of York, UK
Alan Burns	University of York, UK
Giorgio Buttazzo	University of Pavia, Italy
Antonio Casimiro	University of Lisbon, Portugal
Carlos Delgado Kloos	University Carlos III de Madrid, Spain
Johan Eker	Ericsson, Sweden
Joaquim Ferreira	Polytechnic Institute of Castelo Branco, Portugal
Gerhard Fohler	Mälardalen University, Sweden
José Alberto Fonseca	University of Aveiro, Portugal
Josep Fuertes	Technical University of Catalonia, Spain
Marisol Garcia Valls	University Carlos III de Madrid, Spain
Michael Gonzalez Harbour	University of Cantabria, Spain
Giuseppe Lipari	Scuola Superiore S. Anna of Pisa, Italy
Lucia Lo Bello	University of Catania, Italy
Evangelos Markatos	ICS Forth, Greece
Pau Marti	Technical University of Catalonia, Spain
Ernesto Martins	University of Aveiro, Portugal
Miguel de Miguel	Technical University of Madrid, Spain
Laurent Pautet	Telecom Paris, France
Paulo Pedreiras	University of Aveiro, Portugal
Julian Proenza	University of Balearic Islands, Spain
Juan Antonio de la Puente	Technical University of Madrid, Spain



Daniel Simon  
Liesbeth Steffens  
Paulo Verissimo  
Andy Wellings  
Sergio Yovine

INRIA, France  
Philips Research, The Netherlands  
University of Lisbon, Portugal  
University of York, UK  
Verimag Laboratory, France

## **Part IV: Execution Platforms**

Coordinator: Lothar Thiele      ETHZ, Switzerland

Luca Benini  
Geert Deconinck  
Petru Eles  
Rolf Ernst  
Murali Jayapala  
Jan Madsen  
Zebo Peng  
Marco Platzner  
Paul Pop  
Lothar Thiele  
Tom Vander Aa  
Kashif Virk  
Fabian Wolf

University of Bologna, Italy  
K.U.Leuven, Belgium  
Linköping University, Sweden  
Technical University of Braunschweig, Germany  
K.U.Leuven, Belgium  
Technical University of Denmark, Denmark  
Linköping University, Sweden  
ETHZ, Switzerland  
Linköping University, Sweden  
ETHZ, Switzerland  
K.U.Leuven, Belgium  
Technical University of Denmark  
Volkswagen AG, Germany

# Table of Contents

## Part I: Hard Real-Time Development Environments

1	Executive Overview on Hard Real-Time Development Environments.....	1
1.1	Motivation and Objectives .....	1
1.2	Essential Characteristics.....	2
1.3	Role in Future Embedded Systems .....	3
1.4	Overall Challenges and Work Directions.....	4
1.5	Document Structure .....	9
2	Hard Real-Time System Development.....	10
2.1	Brief Discussion of Current Practice: The V-Shaped Lifecycle.....	10
2.2	An Emerging Approach: Platform-Based Design .....	11
3	Current Design Practice and Needs in Selected Industrial Sectors.....	15
3.1	Automotive Systems .....	15
3.2	Aeronautics: A Case Study .....	24
3.3	Consumer Electronics: A Case Study .....	31
3.4	Automation Applications .....	35
4	Tools for Requirements Capture and Exploration .....	39
4.1	Definitions of Hard Real-Time Dependability Features.....	39
4.2	Scientific Engineering Tools and Physical Systems Modellers .....	45
4.3	State-Based Design: Dealing with Complex Discrete Control.....	50
5	Tools for Architecture Design and Capture.....	54
6	Tools for Programming, Code Generation, and Design .....	63
6.1	Structure.....	63
6.2	Code Generation from Synchronous Languages.....	63
6.3	Back-End Code Generation – Below C.....	68
7	Tools for Verification and Validation .....	72
7.1	Building Blocks for Verification and Validation .....	72
7.2	Model Checking .....	72
7.3	Static Program Analysis .....	76
7.4	Testing Embedded Systems .....	80
8	Middleware for Implementing Hard Real-Time Systems.....	85

9	Review of Some Advanced Methodologies .....	92
9.1	The Setta Project .....	92
9.2	The SafeAir Project.....	96

## **Part II: Component-Based Design and Integration Platforms**

10	Executive Overview on Component-Based Design and Integration Platforms .....	103
10.1	Motivation and Objectives .....	104
10.2	Essential Characteristics.....	105
10.3	Role in Future Embedded Systems .....	108
10.4	Overall Challenges and Work Directions.....	109
10.5	Document Structure .....	112
11	Component-Based System Development .....	114
11.1	Lifecycle of Component-Based Systems.....	114
11.2	Lifecycle of Components .....	117
11.3	Issues Specific for Embedded Systems .....	117
11.4	Summary and Conclusions.....	118
12	Current Design Practice and Needs in Selected Industrial Sectors.....	120
12.1	Automotive.....	120
12.2	Industrial Automation .....	124
12.3	Consumer Electronics .....	129
12.4	Telecommunication Software Infrastructure .....	131
12.5	Avionics and Aerospace.....	134
12.6	Summary and Challenges.....	136
13	Components and Contracts.....	139
13.1	Introduction .....	139
13.2	Level 1 – Syntactic Interfaces .....	140
13.3	Level 2 – Functional Properties.....	143
13.4	Level 3 – Functional Properties.....	145
13.5	Level 4a – Timing Properties .....	147
13.6	Level 4b – Quality of Service .....	153
13.7	Specifying and Reasoning About Contracts: Summary and Analysis.....	158
14	Component Models and Integration Platforms: Landscape.....	160
14.1	Widely Used Component Models .....	160
14.2	Component Models for Embedded System Design.....	172

14.3	Integration Platforms for Heterogeneous System Design .....	181
14.4	Hardware/Software Modelling Languages.....	186
14.5	Component Models and Integration Platforms: Summary and Conclusions.....	187
14.6	Component Libraries: Approaches to Component Retrieval.....	189
15	Standardization Efforts.....	194
15.1	Specification Standards.....	194
15.2	Implementation Technology Standards.....	202
15.3	Conclusions and Challenges.....	203
16	References .....	204

### **Part III: Adaptive Real-Time Systems for Quality of Service Management**

17	Executive Overview on Adaptive Real-Time Systems for Quality of Service Management .....	216
17.1	Motivation and Objectives .....	216
17.2	Essential Characteristics.....	217
17.3	Role in Future Embedded Systems .....	218
17.4	Overall Challenges and Work Directions.....	220
17.5	Document Structure .....	225
18	Adaptive Real-Time System Development .....	227
19	Current Design Practice and Needs in Selected Industrial Sectors.....	229
19.1	Industrial Sector 1: Consumer Electronics in Philips.....	229
19.2	Industrial Sector 2: Industrial Automation.....	232
19.3	Industrial Sector 3: Consumer Electronics: Ericsson Mobile Platforms .....	237
19.4	Industrial Sector 4: Telecommunications – The PT-Inovação Case Study.....	240
20	Real-Time Scheduling.....	242
20.1	Landscape.....	242
20.2	Assessment.....	248
20.3	Trends.....	248
20.4	Recommendations for Research.....	252
20.5	References.....	254
21	Real-Time Operating Systems.....	258
21.1	Landscape.....	259
21.2	Assessment.....	275

21.3	Trends.....	279
21.4	Recommendations for Research.....	282
21.5	References.....	283
22	QoS Management.....	287
22.1	Landscape.....	287
22.2	Assessment.....	294
22.3	Trends.....	295
22.4	Recommendations for Research.....	299
22.5	References.....	300
23	Real-Time Middleware.....	305
23.1	Landscape.....	306
23.2	Assessment.....	310
23.3	Trends.....	311
23.4	Recommendations for Research.....	313
23.5	References.....	314
24	Networks.....	316
24.1	Landscape.....	316
24.2	Assessment.....	325
24.3	Trends.....	326
24.4	Recommendations for Research.....	333
24.5	References.....	335
25	Programming Languages for Real-Time Systems.....	338
25.1	Landscape.....	338
25.2	Assessment.....	344
25.3	Trends.....	346
25.4	Recommendations for Research.....	347
25.5	References.....	349
26	Other Issues.....	352
26.1	Power Awareness.....	352
26.2	Media-Processing Applications.....	358
26.3	Integrating Real-Time and Control Theory.....	358
26.4	Probabilistic Time Analysis.....	365
26.5	Hardware Trends.....	369

**Part IV: Execution Platforms**

27	Executive Overview on Execution Platforms.....	373
27.1	Motivation and Objectives .....	373
27.2	Essential Characteristics.....	374
27.3	Role in Future Embedded Systems .....	374
27.4	Overall Challenges and Work Directions.....	374
27.5	Document Structure .....	375
28	Current Design Practice and Needs in Selected Sectors.....	377
28.1	Automotive Industry .....	377
28.2	Mechatronics Industry.....	383
29	Computing Platforms .....	388
29.1	Multiprocessor Systems – Modelling and Simulation.....	388
29.2	Distributed Embedded Real-Time Systems – Analysis and Exploration.....	406
29.3	Reconfigurable Hardware Platforms .....	423
29.4	Software Integration – Automotive Applications.....	440
30	Low Power Engineering.....	450
30.1	Power-Aware and Energy Efficient Middleware .....	450
30.2	Memory Hierarchy and Low Power Embedded Processors.....	464
	Index .....	479