Teaching Embedded Systems Foundations of Cyber-Physical Systems

A (partially) European view

Peter Marwedel
TU Dortmund, Germany
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Cyber-physical systems and embedded systems

CPS = ES + physical environment

Cyber-physical systems

Embedded systems
("small computers")

Embedded systems
("computers in physical environments")

CPS education comprises ES education
Walls between departments must be torn down

Knowledge from many areas must be available,

medicine, statistics, ME, biology, ..
Topics to be taught

Sources include


CPS topics include

- Embedded systems material
- Physics
- Mechanical engineering
- Control
- Math
- Application areas
Requirements according to the ARTIST guidelines

"It seems that fundamental bases are really difficult to acquire during continuous training if they haven’t been initially learned, and we must focus on them."

"The development of ES cannot ignore the underlying HW characteristics. Timing, memory usage, power consumption, and physical failures are important."
“The lack of maturity of the domain results in a large variety of industrial practices, often due to cultural habits”

“curricula … concentrate on one technique and do not present a sufficiently wide perspective.”

“As a result, industry has difficulty finding adequately trained engineers, fully aware of design choices.”
<table>
<thead>
<tr>
<th></th>
<th>Specialization</th>
<th>Separate program</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well-known degrees</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Enough headroom for teaching</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>integrated CPS/ES material</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Headroom for more depth in physics,</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>mechanical engineering, ..</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Effort for introduction</td>
<td>small</td>
<td>large</td>
</tr>
<tr>
<td>No. of faculty members required</td>
<td>moderate</td>
<td>larger</td>
</tr>
<tr>
<td>Building community?</td>
<td>difficult</td>
<td>easier</td>
</tr>
<tr>
<td>Is it feasible?</td>
<td>For ES ok, for</td>
<td>Yes, but there</td>
</tr>
<tr>
<td></td>
<td>CPS</td>
<td>are also</td>
</tr>
<tr>
<td></td>
<td>questionable</td>
<td>constraints</td>
</tr>
<tr>
<td></td>
<td></td>
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</tbody>
</table>
Outline

- Scope
- Requirements for CPS/ES education
  - Linking separate disciplines
  - Artist sources: focus on fundamentals, HW, wide perspective
- ES/CPS education at Dortmund
  - ES/CPS content, context
  - ES/CPS text book, slides, youtube videos
- Education in a larger context
  - Artist(Design) NoE & emsig, Summer Schools, WESE
  - Separate programs (brief)
- Summary
CPS/ES CS undergraduate education at TU Dortmund

- Integrated as a specialization into CS curriculum

- Course structure:
  - Pro-gramming
  - algorithms
  - computer organization
  - OS & networks
  - Math education
  - EE fundamentals
  - Lab
  - Lab (Lego, μC)
  - First course on CPS/ES (in German)
  - + courses for minor degree
  - control systems
  - DSP
  - machine vision
  - real-time systems
  - middle-ware
  - applications
  - + Lab courses for minor degree
  - graduate level
  - thesis
  - project
  - undergraduate
Course content

Application knowledge

- Specification & modeling
- HW components
- System software (RTOS, …)

Design repository

Design

Application mapping

Optimization

Evaluation & verification

Test
Example: Specification and modeling

- Requirements, Models of computation
- Early design phases
  - Use cases, sequence charts
- Communicating finite state machines
  - Timed automata, StateCharts, synchronous languages
  - SDL (as an example of message passing)
- Data flow
  - KPN, synchronous data flow
- Petri nets
- Discrete event based languages
  - VHDL simulation cycle
- Von-Neumann languages
- Levels of hardware modeling, comparison of MoCs
KPN simulation

This training module has been developed for the use as a presentation component in lectures and for the use as a training component in a lab or at home. On the one hand it provides functions for the preparation and demonstration of Kahn Process Network examples. On the other hand it provides an opportunity to recapitulate the basic principles of Kahn Process Networks. Furthermore, you can explore the dynamic behaviour which results from the execution of your own process networks.

By selecting the following links you can find the corresponding information.
Example: CPS/ES hardware

- **Input:**
  - Sensors, discretization

- **Processing**
  - Processors, FPGAs

- **Memories**

- **Communication**
  - Requirements
  - Exemplary implementation: Guaranteeing real-time behavior

- **Output**
  - D/A-converters
  - Sampling theorem

- **Secure hardware (brief)**
Example: Evaluation and Validation

- Multi-objective optimization, Pareto optimality
- Performance evaluation
  - Early phases
  - WCET estimation, real-time calculus
- Energy and power models
- Thermal models
- Risk- and dependability analysis
- Simulation
- Rapid prototyping and emulation
- Formal verification (brief)
Example: Mapping to execution platforms

- Scheduling in real-time systems
  - Aperiodic scheduling
  - Periodic scheduling

- Hardware/software partitioning

- Mapping to heterogeneous multi-processors
  - DOL
## Structure of the CS curriculum at Dortmund
### - 3 year bachelor program -

<table>
<thead>
<tr>
<th>Term</th>
<th>Course(s)</th>
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<th>Course(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Computer organization</td>
<td>Programming &amp; semantics</td>
<td>Math education</td>
</tr>
<tr>
<td>2</td>
<td>Circuits &amp; communication</td>
<td>OS</td>
<td>Algorithms</td>
</tr>
<tr>
<td>3</td>
<td>HW lab</td>
<td>Networks</td>
<td>SW lab</td>
</tr>
<tr>
<td>4</td>
<td>Databases</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Embedded systems fundamentals</td>
<td>Software engineering</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Bachelor project + Thesis</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

All dependences met
Additional teaching elements

- Lab & assignments during course (hierarchical state machines, Mindstorms, scheduling examples)
- Project, optionally in this area
- Bachelor thesis, optionally in this area, optionally in industry
- Courses at the graduate level
  - Software of ubiquitous systems
  - Evaluation
  - ....
CPS/ES robotics and automation graduate education at TU Dortmund

- Specialization of robotics & automation program

B.Sc. in EE, ME, CS, ...

Mostly international students

undergraduate graduate level

Programming
control
computer systems

course on embedded & CP systems (in English)
Experience

- Content of courses is broad and comprehensive
- Extremely popular among students (>100 students @ undergraduate, ~20 students @ graduate course)
- Welcome by local employers
- Limited headroom for advanced topics for undergraduates
- Students sometimes ask for more hands-on experience, but there are tight constraints for this
- No major problems for comprehension (missing prerequisites turned into textbook appendix)
- Heterogeneity of students in robotics program a hurdle
- ES education as a specialization works, but has inherent limitations
Scope

Requirements for CPS/ES education
  • Linking separate disciplines
  • Artist sources: focus on fundamentals, HW, wide perspective

ES/CPS education at Dortmund
  • ES/CPS content, context
  • ES/CPS text book, slides, youtube videos

Education in a larger context
  • Artist(Design) NoE & emsig, Summer Schools, WESE
  • Separate programs (brief)

Summary
Textbook(s)

Several editions/translations:

- 1st edition
  - English
    - Original hardcover version
    - Reprint, soft cover, 2006
  - German, 2007
  - Chinese, 2006
  - Macedonian, 2010

- 2nd edition, with CPS
  - Contracts for German and (translated) Chinese edition
Recorded lectures available on youtube

http://www.youtube.com/user/cyphysystems
Example

Why not use von-Neumann (thread-based) computing (C, C++, Java, ...)?

Potential race conditions (inconsistent results possible)
- Critical sections = sections at which exclusive access to resource \( r \) (e.g. shared memory) must be guaranteed.

```c
thread a {
  ...
  P(S) //obtain lock
  ..  // critical section
  V(S) //release lock
}

thread b {
  ...
  P(S) //obtain lock
  ..  // critical section
  V(S) //release lock
}
```

Race-free access to shared memory protected by \( S \) possible

This model may be supported by:
- mutual exclusion for critical sections
- special memory properties
Selected set of universities using the book

- University of California, San Diego (Tajana Šimunic Rosing)
- Lund Institute of Technology, Sweden (Krzysztof Kuchcinski)
- Universidad De Las Palmas De Gran Canaria (Nunez)
- Politecnico Di Milano (Christina Silvano)
- University of Cyprus (Theocharis Theocharides)
- University of Linköping, Schweden (Petru Eles)
- University of Saskatchewan, Canada (A. Dinh & D. Teng)
- Democritus University of Thrace, Greece (Dimitrios Soudris)
- KIT - Karlsruhe Institute of Technology (J. Henkel)
- TU Berlin (Glesner, Pockrandt)
- TU Braunschweig (Rolf Ernst)
- University of Augsburg (Alexander Knapp)
- University of Kiel (Reinhard von Hanxleden)
- University of Leipzig (Martin Bogdan)
- Hochschule Rhein-Main (Marcus Thoss)
- University of Buenos Aires (Andrés Djordjalian)
- University of Stuttgart (Martin Radetzki)
- University of Tübingen (Lange Tafaj)
- University of Lübeck (Erik Maehle)
- University of Torino (Luciano Lavagno)
- Colorado State University (Sudeep Pasricha)
- Johannes Kepler University, Linz (Alois Ferscha)
- Ruprecht-Karls-University Heidelberg (Udo Kepschull)
- Federal University of Santa Catarina, Brazil (Antônio Augusto Fröhlich)
- Lucian Blaga University, Romania (Macarie Breazu)
- ....
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The Artist Network of Excellence

- Goal: Establish links between top researchers from various domains
- http://www.artist-embedded.org
- Web site a key reference for finding researchers highly qualified research within Europe
- Members agree that establishing links was the key benefit
- Several efforts on education, see http://www.artist-embedded.org/artist/-Education,839-.html
EMSIG, the successor to Artist

- Goals: leverage experiences gained in the Artist network & stimulate future cooperation
- Legally a special interest group of EDAA (the lead organizer of DATE)
- see http://emsig.embedded-systems-portal.org
Artist Summer Schools

Summer schools ([//www.artist-embedded.org/artist/-Schools-and-Seminars,59-.html](//www.artist-embedded.org/artist/-Schools-and-Seminars,59-.html)) are crossing the boundaries between disciplines. They were held at

- Europe
- Latin America
- Asia (China)
- Africa (1)

Continued in cooperation between EMSIG and Nano-Tera (Swiss project), see [//artist-summer-school.epfl.ch/](//artist-summer-school.epfl.ch/), areas:

- Component-based design, efficient computing for CPS, many-core design case, switched network in safety critical systems, medical cyber-physical systems, verification
WESE: Workshop on Embedded (and Cyber-Physical) Systems Education:

- 1st WESE 2005: Jersey City, US, see //www.lulu.com
- 2nd WESE 2006: Seoul, Korea, see //www.lulu.com
- 3rd WESE 2007: Salzburg, Austria, see //www.lulu.com
- 4th WESE 2008: Atlanta, see //www.lulu.com
- 5th WESE 2009: Grenoble, see ACM digital library
- 6th WESE 2010: Scottsdale, see ACM digital library
- 7th WESE 2011: Taipei, see ACM digital library
- 8th WESE 2012: to take place during ESWEEK at Tampere on Oct. 12th, ACM digital library
- 9th WESE 2013: Montreal, Canada, 10/3/2013
Separate programs (samples)

- ALARI @ University of Lugano: master programs (www.alari.ch)
- Joint program of the 3 Dutch Technical Universities (Eindhoven, Twente, Delft): http://www.utwente.nl/master/international/esys/masterprogramme/3tu.doc/
- University of Passau: undergraduate program for mobile and embedded systems, http://www.uni-passau.de/mes.html (in German)
- UPenn (according to info on Monday)
- …

Still open issues for the design of such programs
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