Communication Infrastructure Synthesis and its Application to Cyber Physical Systems: The Intelligent Building case

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Outline

• Societal IT Systems and Cyber-Physical Systems: a Perspective
• The Need for an Integrated Approach to Design: Platform-Based Design
• Communication Synthesis
• Communication Synthesis for Efficient Building Management
The Emerging IT Scene

Infrastructural core

Sensory swarm

Mobile access

Courtesy: J. Rabaey
The Technology Gradient: Communication

Mostly wired

Almost uniquely wireless
Exponentials Bound to Continue

• 5 Billion people to be connected by 2015 (Source: NSN)

• The emergence of Web2.0
  – The “always connected” community network

• 7 trillion wireless devices serving 7 billion people in 2017 (Source: WirelessWorldResearchForum (WWRF))
  – 1000 wireless devices per person?

[Courtesy: Niko Kiukkonen, Nokia]
The Birth of “Societal IT Systems (SiS)” or “Cyber-Physical Systems (CPS)”

“A complex collection of sensors, controllers, compute nodes, and actuators that work together to improve our daily lives”

- The Emerging Service Models
  - Automotive and avionic safety and control
  - Environmental control, energy management and safety in “high-performance” homes
  - Immersion-based work and play
  - Management of metropolitan traffic flows
  - Distributed health monitoring
  - Power distribution with decentralized energy generation
Bottom Line: System Integration

• The Challenge Is NOT in the components themselves, but is Component Integration. This is true for hardware, software, and so/rdware components
  – Solution space exploration almost impossible due to large number of alternatives and lack of adoption of rigorous methods for system-level design
  – Design Validation Remains the Key Bottleneck and is CERTAINLY Getting Even Harder: unpredictable emerging collective behaviors, unexplored corner cases, unforeseen use model.....

• A synthesis approach is essential to solve some of these design problems
Overarching Design Challenge in Integration

<table>
<thead>
<tr>
<th>Yesterday</th>
<th>Features (can you do it?)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Today</td>
<td>Cost (are you cheaper?)</td>
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<tr>
<td>Tomorrow</td>
<td>Integration (but can you also…?)</td>
</tr>
</tbody>
</table>

Industry will move towards robust architectures which can:

- create a system by just interconnecting modules
- mix-and-match components from different vendors
- avoid costly system-level simulations
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Using Platforms: the System Company View

Ideal Application Platform

Application Space

Architectural Space
Separation of Concerns (ca. 1990)

IPs
- Behavior Components
  - C-Code
  - Matlab
  - Dymola
- Virtual Architectural Components
  - CPUs
  - Buses
  - Operating Systems

Development Process
- Specification
- Analysis
- Implementation

Behavior Platform
- Mapping
- Performance Analysis
- Refinement
- Evaluation of Architectural and Partitioning Alternatives
**Platform-Based Design**

- **Platform**: library of resources defining an abstraction layer
  - Resources do contain virtual components i.e., place holders that will be customized in the implementation phase to meet constraints
  - Very important resources are interconnections and communication protocols
“Platform-based design greatly reduces time, cost and overall design risk for developing derivative products, as well as providing the framework for responding quickly to future technologies and changing market requirements. Our newest SoC device for the digital TV market stands shoulder to shoulder with industry leaders in every core technology from picture quality, performance, data processing, speed, and specialized design architecture”

- Don H. Lee, Senior Vice President
  ASPDAC Key Note Address
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- Societal IT Systems and Cyber-Physical Systems: a Perspective
- The Need for an Integrated Approach to Design: Platform-Based Design
- Communication Synthesis (GM, Intel, UTC, Telecom Italia, Pirelli)
- Communication Synthesis for Efficient Building Management
Communication Synthesis Infrastructure (COSI) Methodology

• Capture metrics of interest with *quantities* (performance and constraints)
  – Partially ordered sets

• Define *communication structures* as components annotated with quantities
  – Function, Platform Instance, Implementation

• Define a *platform*
  – Library of components, Composition rules

• Develop *algorithms*
  – Given a function and a platform find the best mapping of the function onto a platform instance
Latency Requirements in Distributed Systems

- Automotive
- Aeronautics
- Elevators
- Building automation
- Industrial automation

Elevators
Design Flow for optimizing distributed systems with latency constraints

Application

IR Sensor
Wheel Sensor
Nav. Task
Fusion Task
Object ID Task
Brake Actuator
Throttle Actuator

Architecture

ECU1
CAN1
ECU2
CAN2
ECU3
ECU4

150 ms
225 ms

Mapping

Implementation

Design Space

Allocation
Priorities
Periods
Activation Model
Extensible Mathematical Programming Approach

Extensibility to add additional constraints for system-specific situations

Design Space
- Allocation
- Priorities
- Periods
- Activation Model

Mathematical Programming Based Approaches

Geometric Programming (GP)
- Period Synthesis
  - DAC 2007 BEST PAPER AWARD

Mixed Integer Linear Programming (MILP)
- Activation Model Synthesis
  - DATE 2007 Nomination BPA
  - RTSS 2007 BEST PAPER AWARD
- Allocation and Priority Synthesis

Copyright: A. Sangiovanni-Vincentelli
Communication Design
(e.g., NOCs, Wireless-Wired Automation Control)

Component: Nodes (can be sub-net with access interfaces)
Quantities: Max number of flows, max number of ports, max bandwidth, delay, services (MAC, Network, Physical), Power consumption
Cost: Installation and maintenance

Component: Links
Quantities: Maximum length, Max bandwidth, Minimum PER, Delay
Cost: Installation and maintenance

End-to-end Latency, Bandwidth, PER Redundancy

Implementation:
A network that guarantees all end-to-end constraints at minimum installation an operation cost

✓ Implement end-to-end communication on a multi-hop network
✓ Characterize components (nodes, links, sub-nets)
✓ Synthesis

 Courtesy: A. Pinto
## The COmmunication Software Infrastructure (COSI) Design Package

**Software Organization**

**Courtesy: A. Pinto**
Outline

• Societal IT Systems and Cyber-Physical Systems: a Perspective
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• Communication Synthesis for Efficient Building Management
U.S. Buildings consume
- 39% of total U.S. energy
- 71% of U.S. electricity
- 54% of U.S. natural gas

U.S. Buildings produce 48% of Carbon emissions


Commercial Building Energy Intensities are increasing
- Electrical Energy consumption doubled in last 18 years
- 25% growth projection through 2030
High Performance Buildings: the Problem

Objectives: Efficient energy utilization and occupant comfort for normal building operation
Robust response to health and safety threats and events

Energy & mass balances govern steady-state building energy performance
“Slow” non-local coupling from air movement system

- Large, spatially distributed system
- Interconnected system
  - Room neighborhood scale
  - Building floor scale
  - Whole building scale
- Multi-scale dynamic system & its control
  - Wide time scale separation
  - “Close” coupling leading to dynamic constraints between network and physical system

Multi-zone, steady/quasi-steady behavior at intermediate scales relevant to occupant comfort and safety

“Fast” non-local coupling over communication/control network for response to transient events

Spatiotemporal airflow dynamics at room scale relevant to safe building environment
Integrated Design of Building Automation Systems

Multi-scale, Multi-Agent, Potentially Distributed Hybrid Control System

Middleware
- Query, Location, Time, Naming
- Transport level commands, Scheduling
- End-to-end QoS: Interoperability, Addressing and Routing, MAC, Power Management

Platform Instance + Mapping

Implementation

1. Heterogenous
2. Fault Tolerant
3. QoS Guaranteed
4. Cost Effective

Courtesy: A. Pinto
Distributed Control Design

Component: Controller
Quantities:
- Maximum size of state space
- Maximum number of ops

Component: Variable
Quantities:
- Maximum number of doubles/int

Implementation:
A set of controllers communicating over shared variables such that control properties are maintained and cost is minimized

Formal Description of Specification
Characterization of resources
Synthesis

 Courtesy: A. Pinto
Comm/Comp Trade-Off

Component: Electronic Control Unit
Quantities: Memory, computation speed, power consumption
Cost: Installation and maintenance

Component: Communication
Quantities: End-to-end QoS (bandwidth, delay, PER, distance)
Cost: Abstraction of network cost (installation and maintenance)

Implementation
A set of ECU, their position such that the sum of computation and communication cost is minimized

✓ Distribute control on ECUs
✓ Characterize performance and cost of controllers and communication effort
✓ Synthesis

Courtesy: A. Pinto
Communication Design

Position

End-to-end Latency, Bandwidth, BER
Redundancy

Component:
Nodes (can be sub-net with access interfaces)
Quantities:
Max number of flows, max number of ports, max bandwidth, delay, services (MAC, Network, Physical), Power consumption
Cost:
Installation and maintenance

Component:
Links
Quantities:
Maximum length, Max bandwidth, Minimum PER, Delay
Cost:
Installation and maintenance

Implementation:
A network that guarantees all end-to-end constraints at minimum installation an operation cost

✓ Implement end-to-end communication on a multi-hop network
✓ Characterize components (nodes, links, sub-nets)
✓ Synthesis

Courtesy: A. Pinto
Putting It All Together

Proposed design flow for UTRC networked control systems

Communication Synthesis
The Library of Communication Components

- Twisted-pair wires
  - Daisy-chain connection
  - ARCNET protocol (token ring bus)

- Wireless communication channels
  - Tree topology
  - ZigBee (802.15.4)
Examples

ZigBee Technology
BO = 7, SO = 3
$27000 over 20 yr
Max end-to-end latency = 2s
Max PER = 1e-5

Courtesy: A. Pinto
Results

- L-Buildings: 70 x 30 m^2, 64 nodes, period=0.1s, b=16 bits

- Big-box office: 60 x 56 m^2, 64 nodes, period=0.1s, b=16 bits

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<th>Bw (Kb/s)</th>
<th>Max Length (m)</th>
<th>Max #devices</th>
<th>Max delay (ms)</th>
<th>Max Utilization (%)</th>
<th>Router ($)</th>
<th>Nodes ($)</th>
<th>Wires ($)</th>
<th>Total ($)</th>
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New

Retrofit
Conclusions

• A PBD-based design flow for CPS
  – Algorithmic analysis
  – Technology aware partitioning
  – Binding to computation resources
  – Communication synthesis

• Building automation system as an important application domain

• System for Off- and on-line management of large buildings as a final result