Energy-Aware Computing Systems

Energiebewusste Rechensysteme

VI. Cyber-Physical Systems

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Agenda

Preface

Terminology

Dynamic System Structure Partitioning Cross-System Control

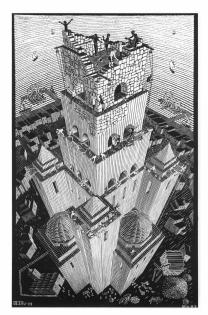
Cyber-Physical Systems Resource Demand Communication Control

Summary



Preface: Pluralism of Systems

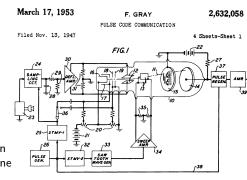
- broader perspective
 - introversive perspectives at the level of individual systems
 - holistic perspective at a higher level of compound systems
- dependence and cooperation
 - individual systems specialize in specific tasks of the compound system
 - cooperation between individual systems to form a (even) greater "whole"





Abstract Concept: Cyber-Physical Systems

- cyber-physical systems
 - digital operations that interface with the physical world
 - computation
 - sensing of data
 → pre-processing
 - processing of data
 - communication
 - transformation of data
 - data transmission
 - uni- and bidirectional
 - control
 - control loops
 - several levels of abstraction (i.e., cruise control, machine control, injection control)



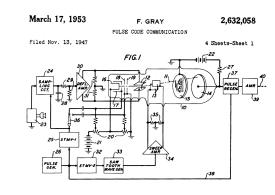


Abstract Concept: Cyber-Physical Systems

- cyber-physical systems
 - physical operations that interface with the digital world
 - natural systems
 - hydrologic cycle
 - solar system
 - human-made systems

 - optical systems
 - $\hookrightarrow \mathsf{light} \; \mathsf{energy}$
 - electrical systems
 - \hookrightarrow electrical energy

tools, instruments etc.

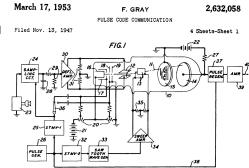




Abstract Concept: Cyber-Physical Systems

cyber-physical systems

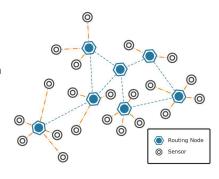
- systems that interlock cyber systems with physical systems
- integrate systems
 - combine physical systems and processes
 - incorporate with networked computing infrastructure
- enhance functionalities
 - augment features of physical systems
 - new capabilities due to computing and communications
- broad range
 - deeply embedded systems (i.e., pace maker)
 - large scale industry facilities (i.e., power plant)





Dynamic Structures

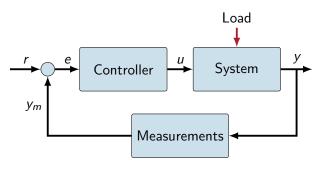
- composition of system is dynamic
- variable system structure depends on time and location
 - spontaneous joining and resignation of devices
 - overload and breakdown detection
- heterogeneous network links
 - wired and wireless links with variable channel conditions
 → propagation, delay loss
 - impact of (physical) system components on link quality



Nunes et al.



measurement-based analysis with a feedback control system



- controller operates system: **closed control loop** ⇒ feedback control
- control: control variable u measure: process variable y



Cyber-Physical System Control

- cyber-physical control systems: use hardware "in a loop"
 - information on physical environment ← sensors
 - sample-and-hold-circuits and analog-to-digital (A/D) converters: digital representation of physical aspects
 - $lue{}$ compute and control ightarrow actuators

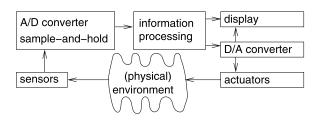


Figure 3.2. Hardware in the loop



Nested Cyber-Physical System

- nested controls that operate jointly in a broader context
 - control: actuator controls physical plant
 - sense/feedback: physical interface towards sensors

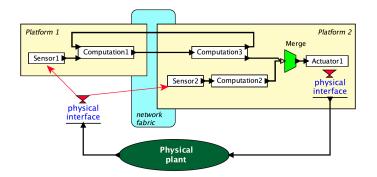


Figure 1.1: Example structure of a cyber-physical system.

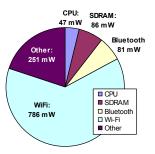


Resource Demand

- energy as a basic operating resource of embedded systems that constitute main parts of a cyber-physical system
- computation
 - general purpose CPUs
 - (re{configur,programm}able) application-specific integrated circuits
- communication
 - lacktriangleright transmission power for (wireless) network links o tail state analysis
 - (periodic) duty cycles
- control
 - actuators
 - cross-layer operations → cyber-physical networking



- network communication contributes significant shares to the overall energy demand
 - state-dependent power demand
 - activity tracking across different subsystems (i.e., application logic, network stack, hardware)



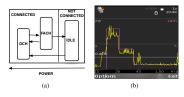
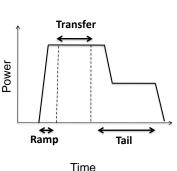


Figure 1: : (a) The radio resource control state machine for 3GPP networks consisting of three states: IDLE, DCH and FACH (b) Instantaneous power measurements for an example transfer over 3G showing the transition time between high to low power state



tracking of tail states to schedule the execution of requests (e.g., packet transmission)



TailEnder scheduler (t, r_i, d_i, a_i) :

- 1. Let Δ be the last deadline when a packet was transmitted (initialized to $-\infty$ and reset in Step 3(c)).
- 2. If $(t < d_i)$
 - (a) if $(\Delta + \rho \cdot T < a_i)$, transmit.
 - (b) else add the request to queue Q.
- 3. If $(t == d_i)$
 - (a) Transmit r_i
 - (b) Transmit all requests in Q and set Q = null
 - (c) Set $\Delta = d_i$

Figure 10: The TailEnder algorithm decides at time instant t whether to transmit a request r_i with arrival time a_i and dead-line d_i . The parameter ρ is set to 0.62 in our implementation.



Control Mechanisms in Cyber-Physical Systems

- Ptides: A Deterministic CPS Modeling Paradigm (UC Berkeley)
- system modeling assumptions
 - synchronized clocks with known bound on synchronization error
 - communication channels with known bounds on latency
 - computations impacting the physical world have known bounds
- Interlude: Latency and Resilience-aware Networking (LARN)
 - pragmatic approach for designing low-latency cyber-physical systems
 - suitable for control applications in cyber-physical systems
 - X-Lap: tool-based cross-layer analysis method



LARN: Context

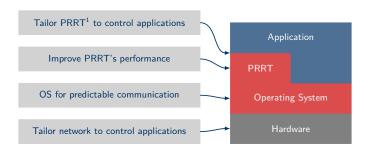


- ▶ DFG Priority Programme Cyber-Physical Networking (SPP 1914)
 - ▶ focus: predictable latency and resilience in cyber-physical networks
 - ▶ interdisciplinary: computer science, electrical and control engineering
 - ▶ 11 individual projects, funding for six years (planned)
 - ▶ http://www.spp1914.de
- ► Target scenario: control applications
 - system control in industrial facilities (e.g. BMW etc.)
 - low-latency control loops for medical applications
 - wireless sensors and network transports
- ► Latency- and Resilience-Aware Networking (LARN)
 - ▶ operating system: System Software Group at FAU Erlangen-Nürnberg
 - transport protocol: Telecommunications Lab at Saarland University
 - http://larn.systems



LARN: Overview and Project Goals



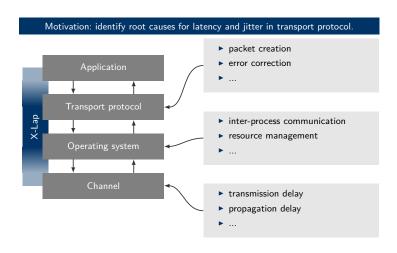




¹predictably reliable real-time transport

X-Lap | Introduction







X-Lap | Architecture



online analysis at run-time

- ▶ timestamping functions
- ⇒ timestamps
- ► C implementation

- ► trace every packet
- embedded into transport protocol code

offline analysis

- data analysis
- ⇒ latency and jitter
- Python implementation



X-Lap | Architecture

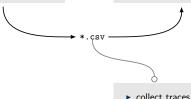


online analysis at run-time

- timestamping functions
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- ▶ C implementation

offline analysis

- data analysis
- ⇒ latency and jitter
- Python implementation



- combine trace data



X-Lap | Architecture



online analysis at run-time

- timestamping functions
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offline analysis

- ▶ data analysis
- ⇒ latency and jitter
- ▶ Python implementation

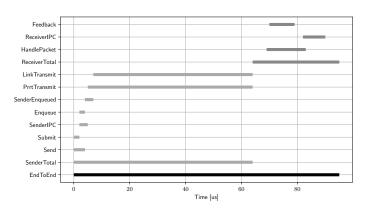


- ▶ single-packet traces
- jitter amongst packets
- outlier analysis
- correlation analysis



X-Lap | Packet Trace

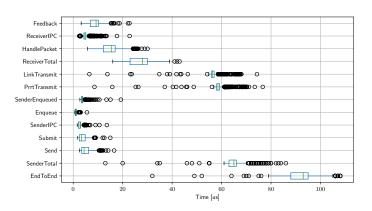






X-Lap | Trace Jitter







Evaluation Platform



Autonomous Driving Car using RNAs

- ► Raspberry Pi 3 (w/ 802.11n)
- ▶ camera CCD
- ultrasonic sensors
- chassis and motor



Autonomous Driving (line following)

- camera captures line and transmits video via PRRT
- edge controller extracts line, determines angle, and determines control outputs
- target speed transmitted back and applied on the motor
 - edge-to-car communication

Platooning (car following)

- ▶ first car follows line
- second car follows and keeps distance to first car
 - car-to-car communication



Results and Outlook



- ▶ Improve cross-cutting system properties
 - ▶ focus on energy efficiency: impact of runtime adaptations
 - non-functional properties of networked systems (i.e. RNAs)
 - system configuration of individual RNAs (i.e. local scope)

energy demand/latency of overall system (i.e. global scope)



- ▶ Identification and proactive avoidance of bottlenecks within system stack
 - build "strain reliefs" to avoid emergence of bottlenecks
 - proactively exploit a priori knowledge (i.e. system design)
 - cooperative system-analysis (i.e. ahead of runtime + at runtime)



Results and Outlook



CCNC 2019 Workshop

IEEE Workshop on Cyber-Physical Networking (CPN'19), January 2019, Las Vegas http://cpn2019.spp1914.de/

Publications

- Reif, Stefan; Schmidt, Andreas; Hönig, Timo; Herfet, Thorsten; Schröder-Preikschat, Wolfgang: "Differential Energy-Efficiency and Timing Analysis for Real-Time Networks", 16th International Workshop on Real-Time Networks (ECRTS RTN), Barcelona, Spain, July 2018
- Reif, Stefan; Hönig, Timo; Schröder-Preikschat, Wolfgang: "In the Heat of Conflict: On the Synchronisation of Critical Sections", IEEE International Symposium on Real-Time Distributed Computing (ISORC), Toronto, Canada, May 2017
- Reif, Stefan; Schmidt, Andreas; Hönig, Timo; Herfet, Thorsten; Schröder-Preikschat, Wolfgang: "X-Lap: A Systems Approach for Cross-Layer Profiling and Latency Analysis for Cyber-Physical Networks", 15th International Workshop on Real-Time Networks (ECRTS RTN), Dubrovnic, Croatia, June 2017



Considerations and Caveats

- cyber-physical systems
 - complex digital systems that interfere with physical world
 - dynamic system structure
 - embedded systems sense and actuate in a networked compound
- energy demand of cyber-physical systems
 - computation
 - ullet communication o consideration and active exploitation of tail states
 - ullet control o cross-layer analysis



Subject Matter

- cyber-physical systems are a corner stone for large-scale control systems that connect digital with physical components
- single embedded systems are joining in a dynamic, networked compound to build an **(even)** greater "whole"
- energy demand considerations are pervasive → influence on other non-functional properties of the cyber-physical systems (i.e., reliability, resilience)
- reading list for Lecture 7:
 - ► Andrew Krioukov et al.

NapSAC: Design and Implementation of a Power-Proportional Web Cluster

Proceedings of the Workshop on Green Networking (GreenNet'10), 2010.



Reference List I

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 - In: Proceedings of the SIGCOMM Conference on Internet Measurement (IMC'09), 2009 (IMC '09), S. 280–293
- [2] LEE, E. A.; SESHIA, S. A.: Introduction to Embedded Systems: A Cyber-Physical Systems Approach. The MIT Press, 2016. – ISBN 978-02-625-3381-2
- MARWEDEL, P.:
 Embedded System Design Embedded Systems Foundations of Cyber-Physical Systems.

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