New World of Opportunities: CPS, IOT, and Beyond

Calton Pu
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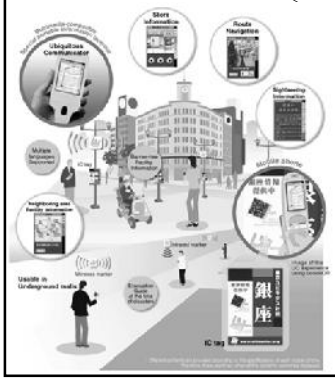
Slide credits: many universities and companies, talks by others

1

Ubiquitous Computing



- One of the few lasting successful predictions/vision in computer science
  - Mark Weiser (around 1988)

2

UbiComp's Secret: Technology Push

- Moore's law
  - Miniaturization and cost reduction of computers
  - Evolution of supercomputers and clusters
- Increasing bandwidth of wired networks
- Wireless networks
  - Sensors (self-reporting)

3

Evolution of UbiComp

- Pervasive computing
  - Systems community
- Ambient Intelligence
  - EU (Philips, since 1998)
  - Nano-tera.ch (Switzerland, since 2009)
- Internet of Things (IOT)
  - China (premier J. Wen, since 2009)
- Cyber Physical Systems (CPS)
  - USA (NSF program, since 2006)

4

Cyber Physical Systems Vision

- Cyber + Physical
  - Cyber = Big Data and models encompassing "all of knowledge"
  - Physical = real-time monitor and control of physical world phenomena
- What's new?
  - *Bending space and time for social, economic, and human benefits*

5

Evolution of Health Care

- Past: disease care and management
- Current: personalized health care
- Future: CPS for health care



6

Example: Chronic Heart Disease

- Chronic diseases are the most common and costly health problems:
  - Heart, cancer, diabetes, arthritis, stroke
- Current state of art in cardiac arrest
  - Automated external defibrillators (AED)

7

Smarter Health Care

- Startup company (Pred. Med. Tech.)
  - Large data set of arrhythmia data before heart attack (tens of thousands of patients)
  - Real-time monitoring of heartbeats in ICU
  - Prediction of cardiac arrest up to 24 hours before it happens (in ICU)

8

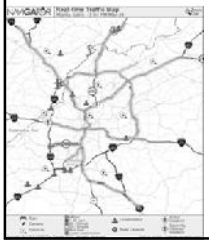
CPS Scenario (Healthcare)

- For you and me:
  - Huge data sets of arrhythmia data before heart attack (millions of patients)
  - Real-time monitoring by wearable sensors
  - Accurate alert of impending heart attack 30 minutes before the attack (*time warp*)

9

Evolution of Intelligent Transportation

- 1996: fixed sensors (Georgia-Navigator)
- 2010: 511-Live, Google maps
- Future: CPS for transportation



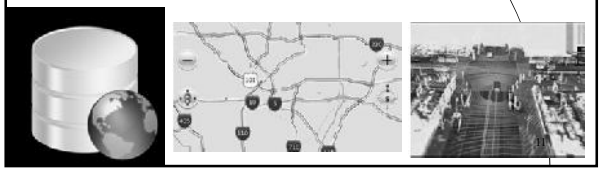
Expensive specialized sensors, highway only

Mainly mobile phones, highway and local roads

10

CPS Scenario (Transportation)

- Predictive navigation, automated driving
  - Huge data sets on traffic data and people's usual routes, travel times
  - Real-time monitoring of traffic and knowledge of planned routes
  - Automated driving along route with predictive time (e.g., reserved highways, *space warp*)



11

Evolution of Electrical Grids

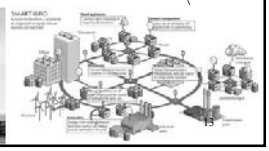
- Past: centralized utility companies
- Current: automated fine-grain monitoring of household usage
- Future: CPS for smart grid

12

CPS Scenario (Smart Grid)

- Huge data sets on electricity consumption patterns by each building and household
- Real-time monitoring and control of electricity distribution (e.g., anti-synchro)
- Predictable, more efficient global usage at lower individual costs





13

Smart Buildings

German Reichstag (Berlin)

Wind Powered Rotating Towers of Dubai (proposed)

Kuala Lumpur's Precinct 4 (proposed)


14

Evolution of Smart Buildings

- Past: increasing amount of technology
- Current: sensors and controls for green buildings (energy management)
- Smart bridges: sensors for structural integrity, failure prediction, disaster recovery



15

CPS Scenario (Smart Buildings)

- Huge simulation data on building and bridge behavior under stress
- Many kinds of sensors
  - Thermometers for cooling/heating, thermometers for mapping fire
  - Environmental: CO_2, light, noise, etc
  - Accelerometers and GPS (vibration, building stability, structural integrity)
- Control internal environment and predict building stability/integrity

50% prob. building collapse in 30 min

16

Evolution of Food Safety

- Past: food problems known (E. Coli, salmonella), sources often unknown
- Current: after the fact detection from sufficiently widespread epidemic outbreaks
- Future: CPS for food safety

17

Salmonella Outbreak 2008

- Salmonella outbreak (USA, 2008-09)
  - 9 deaths and 691 people sick in 46 states
  - Traced to 2 peanut butter plants by epidemiological analysis and lab tests
  - Most extensive food recall in US history: by April 2009, it involved 361 companies and 3,913 different products
- Food safety an important problem and it should be preventive

18

CPS Scenario (Food Safety)

- Detection at source (producer)
  - Sampling for radiation, bacterial, other contaminations
- Processing/test (distributor)
  - Comprehensive testing at stores
- Food lifetime guarantee
  - Packaged biosensor + RFID (consumer)

19

Bending Space and Time

- Health care
  - Predict heart attacks before they happen
- Intelligent transportation
  - Get you home at guaranteed time
- Smart grid/buildings/bridges
  - Lower cost *and* better service
  - Self-monitoring for stability and integrity
- Food safety
  - Prevent contamination with biosensors

20

CPS: Vision vs. Program

- Some numbers from NSF award search (CPS, active = 2009+2010)

Summary of CPS awards in 2009 and 2010 (in dollars)

Grant Category	Grants Awarded	Smallest Award	Largest Award	Average in Category	Total by Category
Large	5	1,283,688	2,400,000	1,810,349	9,051,746
Medium	59	100,000	1,515,525	772,389	45,570,937
Small	52	94,848	600,000	404,036	21,009,888
Grand Total 2009-2010					75,632,571

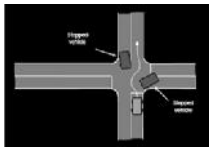
21

Largest CPS Project

- Center for Autonomous Transportation Systems
  - PI: Raj Rajkumar (CMU, $2.4M/4Y)
- Enable automobiles to be driven autonomously
  - Reliable, safe and timely operations inside the automobile
  - Physical conditions and uncertainties in the external environment
  - Real-time communications
  - Verification and validation technologies

22

Aviation and Automotive Systems



CPS: Medium: Autonomous Driving in Mixed-Traffic Urban Environments

Umit A Ozguner, Ashok K Krishnamurthy, Fusun Ozguner, Paolo A Sivilotti, Bruce W Weide (Ohio State U)

Figure: An intersection situation from the 2007 DARPA Urban Challenge (a) as originally described, and (b) simplified for consideration in the rules.

Health and Medicine (1)

CPS Small: Control of Surgical Robots: Network Layer to Tissue Contact

Blake Hannaford, Howard J Chizeck (U Washington)

Intelligent tele-surgery in which a surgeon, or a distributed team of surgeons, can work on tiny regions in the body with minimal access.

Deployment in a tent (top photos)in California (High Altitude Platform, Mobile Robotic Telesurgery (HAPs/MRT)), and deployment in an underwater habitat

Health and Medicine (2)

CPS:Medium: Programmable Second Skin to Re-educate Injured Nervous Systems

Eugene C. Goldfield (Harvard Medical School, Children's Hospital Corp), Rob Wood and Radhika Nagpal (Harvard University), Dava Newman (MIT), Marc Weinberg (Draper), Kenneth Holt and Elliot Saltzman (BU)

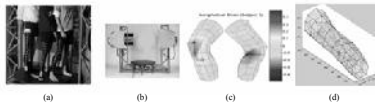
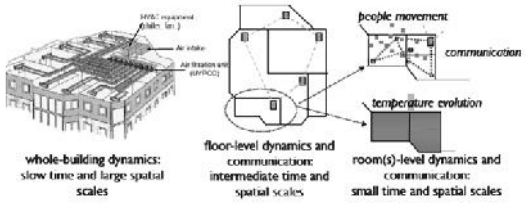


Figure: (a) Colored markers on subjects' legs serve as fiduciary marks to measure skin strain as the legs are flexed during (b) laser scan data acquisition. (c,) A resulting skin strain field calculation showing up to ±40% longitudinal strains. (d) Sample lines of non-extension.

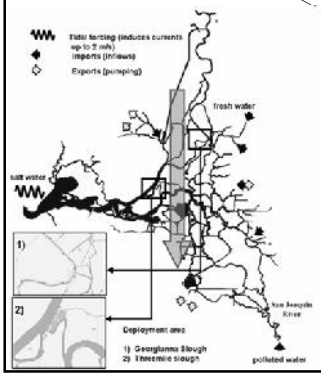
Energy and Environment (1)

CPS: Medium: Collaborative Research: GOALI: Methods for Network-Enabled Embedded Monitoring and Control for High-Performance Buildings

Prabir Barooah (U. Florida), Alberto Speranzon (UTRC), Prashant Mehta and Sean Meyn (UIUC), Luca Carloni (Columbia)



Energy and Environment (2)



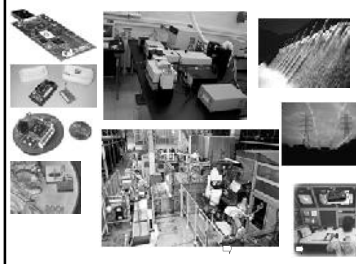
CPS:Medium:Collaborative Research: Physical Modeling and Software Synthesis for Self-Reconfigurable Sensors in River Environments

Jonathan Sprinkle (U. Arizona), Sonia Martinez (UCSD), Alex Bayen (UC Berkeley)

Closing the loop in the Delta: freshwater corridor management using gates operated on a tidal timescale based on Lagrangian/Eulerian sensing.

Center for Hybrid and Embedded Software Systems (UC Berkeley)

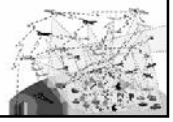
CPS Vision: Reliable and Evolvable Networked Time-Sensitive Computational Systems, Integrated with Physical Processes



Where CPS Differs from Embedded Systems

The embedded systems problem: Embedded software is software on small computers. The technical problem is one of optimization (coping with limited resources).

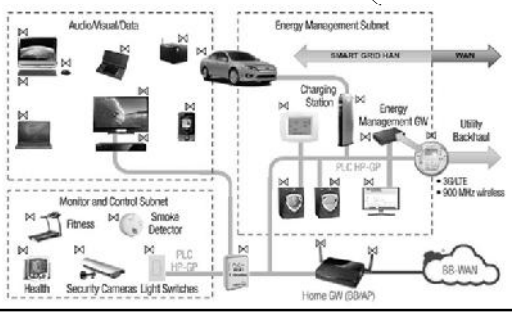
The CPS problem: Computation and networking integrated with physical processes. The technical problem is managing time and concurrency in networked computational systems.



February 21, 2008

Internet of Things (IOT)

- Similar vision, different names



29

Major IOT Initiatives

- IERC (EU Research Cluster on Internet of Things) www.internet-of-things.eu.
  - Many projects: IoT-i (Internet of Things Initiative), IoT-A, Auto-ID Labs
- Nano-tera.ch (Switzerland, 2009)
- Wisdom of Earth vision (Wen J., 2009)
  - Wuxi Institute of Internet of Things
  - China Mobile Wuxi IoT Institution
- Smarter Planet (IBM, Palmisano, 2008)

30

IERC Research

- Design and integration of objects
  - Energy management; packaging and integration; deployment and calibration; trust, security, robustness; reconfigurable objects
- Massive secure and flexible networking of objects
  - Communications protocols; quality of services; middleware; geo-location and privacy
- Service management
  - Local data fusion; distribution and heterogeneity; ambient intelligence

31

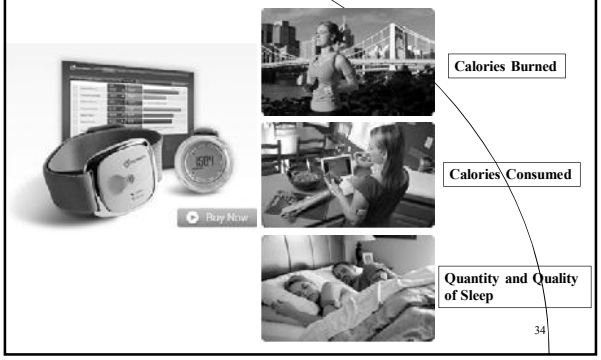
CPS/IOT Conferences

- CPS Week (April each year, US)
  - HSCC, ICCPS, IPSN, LCTES, and RTAS (hybrid/embedded systems, sensor networks, CPS, real-time)
- IoT Week 2011 (IERC)
  - June 6-9, 2011, Barcelona
- IoT China 2011
  - June 16-17, 2011, Shanghai
- IoT 2010 Conference (Nov 29-Dec 1, Tokyo)

32

IBM: Smarter Industries

Health Monitor Product



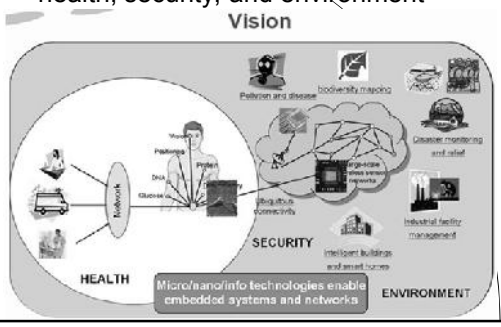
34

CityOne Simulation Game

- Teaching and learning complex systems
  - For city planners and managers
  - Management of resources: electrical grids, water management, …

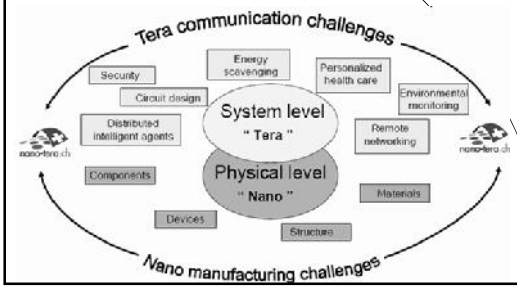
nano-tera.ch (Switzerland)

- Engineering complex systems for health, security, and environment



Many Research Challenges

- Similar vision, more focused



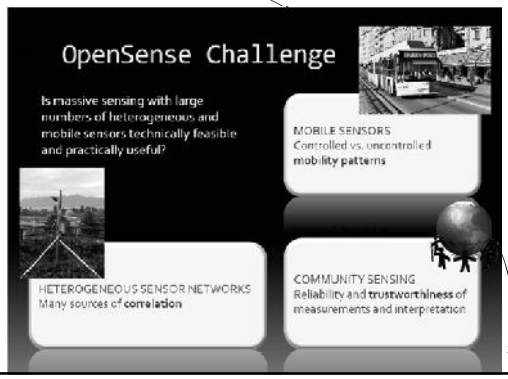
37

Program Execution

- About CHF$120M, 2009-2012
  - 19 RTD (large projects, up to CHF$1M/Y)
  - 32 NTF (small projects, up to CHF$500K)
  - ED (educational projects)
- To be announced: nano-tera Phase 2 and 3 (up to 2020)
  - Technology development and industry impact
  - Clear perception of success and enthusiasm

38

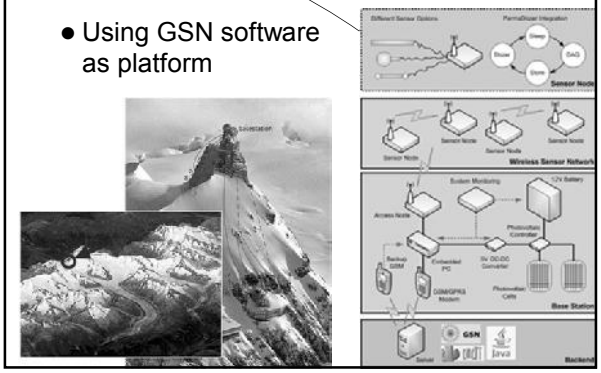
OpenSense: Environ. Monitoring



39

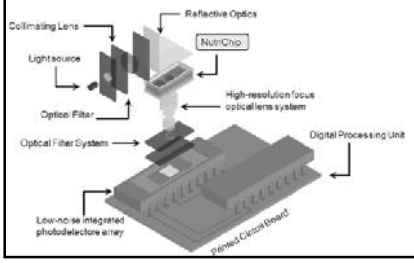
X-Sense: Glacier Monitoring

- Using GSN software as platform



Nutrichip: monitoring health

- Lab-on-chip to emulate digestion of dairy products regarding immuno-modulatory properties



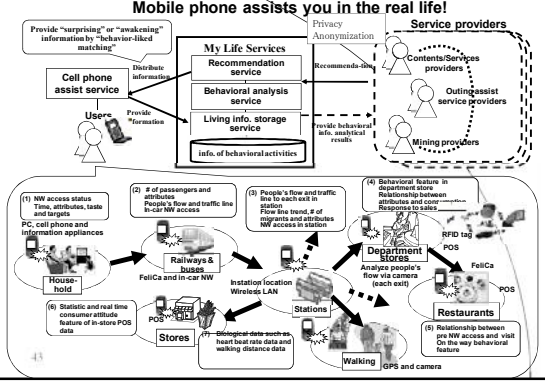
41

Funding Programs in Japan

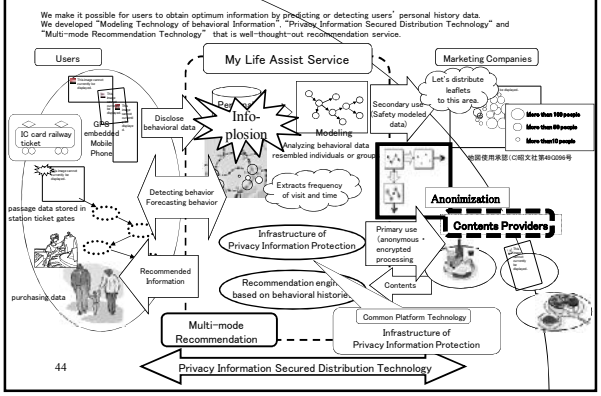
- Information Grand Voyage Project (shared by several companies, 2007 – 2010) $130M funded by METI
- Info-plosion Project (shared by hundreds of researchers, 2005 – 2011) $30M by funded by MEXT
- FIRST (lead: U. Tokyo + several universities, 2010 – 2014) $42M funded by JSPS
- Planned new CPS Japan program

42

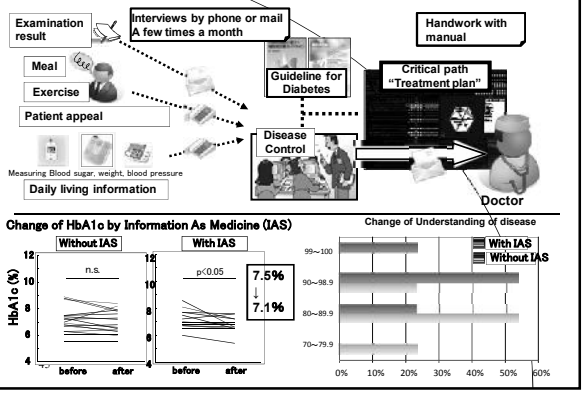
Mobile Service: My Life Assist (NTT DoCoMo)



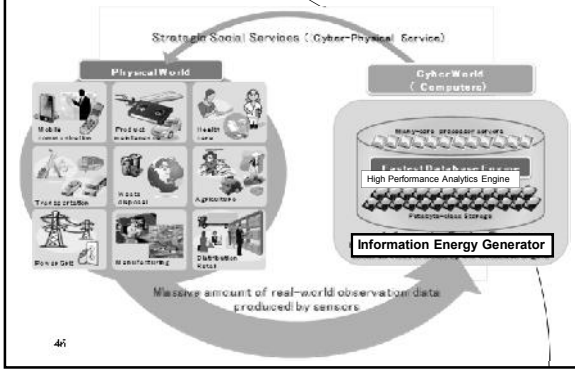
My Life Assist Service NTT DOCOMO, Inc.



Information As Medicine for Diabetes



New Project FIRST (2010~)



Building CPS/IOT Systems

- Hardware: part of technology push
  - More powerful and economical
- Software: challenge and bottleneck
  - Current programming models and languages are mainly sequential and process-oriented
  - End-to-end quality of service difficult to add
  - Adaptation affects the entire system
  - Expensive verification and validation

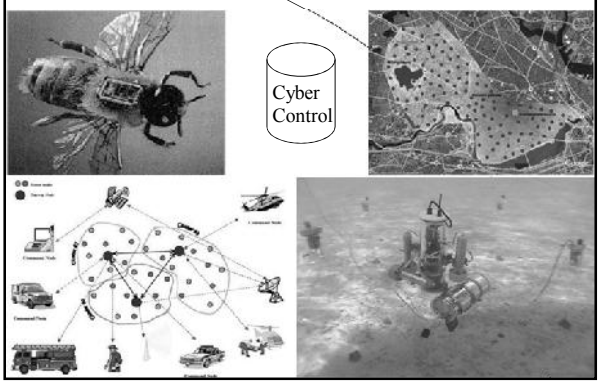
47

New York-centric View of World

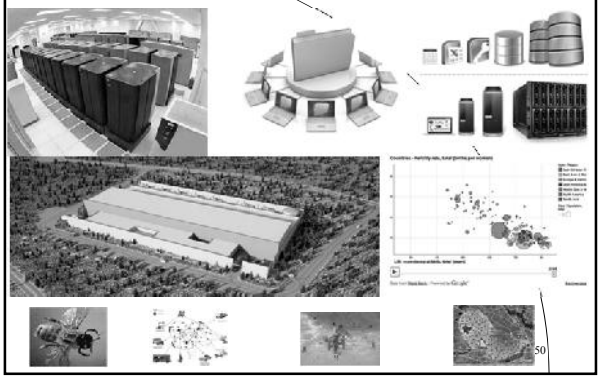
- It's natural to see the world from our personal perspective
- Same with CPS

48

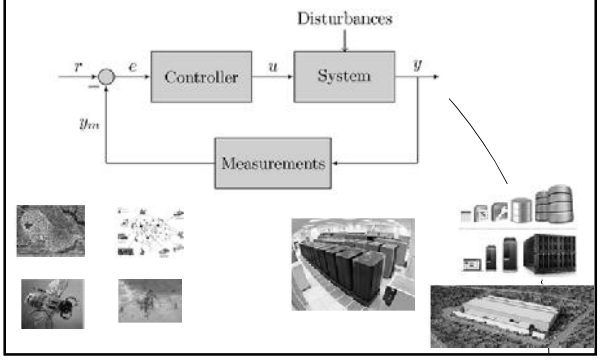
Sensor Network View of CPS/IOT



Database View of CPS/IOT



Control System View of CPS/IOT



Event View of CPS/IOT

- Clearly there are events of interest
  - Prediction of heart attack
  - Prediction of traffic congestion
  - Prediction of building failure
  - Prediction of electricity consumption
- But there is more….

52

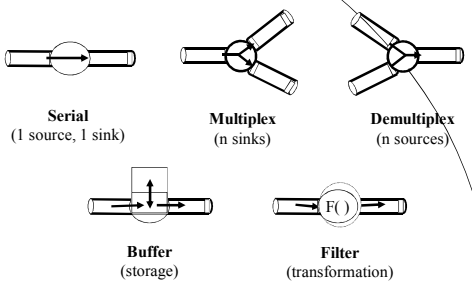
System Composition Techniques

- Some limitations of current software due to process view
  - State explosion in verification & validation
- Events may offer alternative ideas
  - Data flow (example: Infopipes)
  - Distributed events (example: Continual Queries)
  - WED-flow (Workflows, Events, Data-flows)

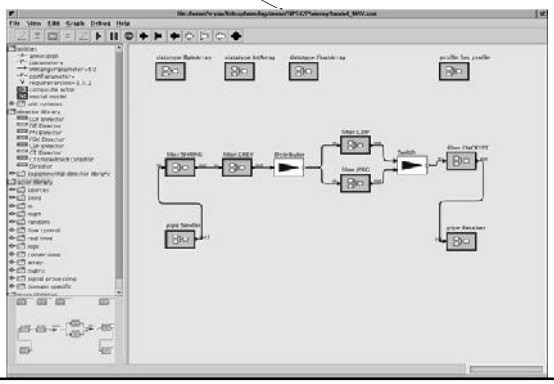
53

Infopipes: Data-Centric Processing

- Types of Infopipes

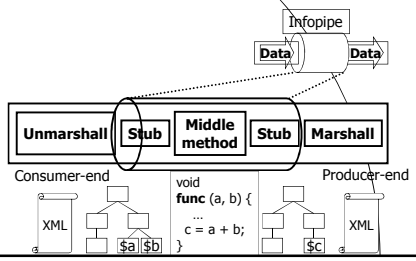


Infopipe Specification



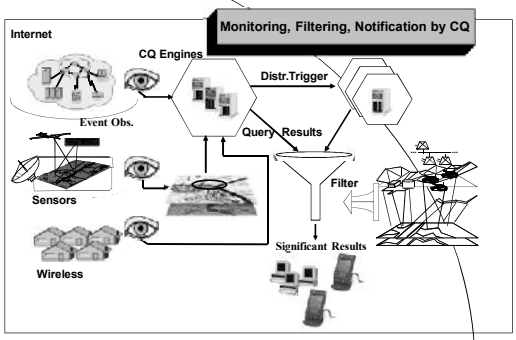
Infopipe - A Look Inside

- Mapped to general languages (C++, Java)
- Generate stub/marshalling code

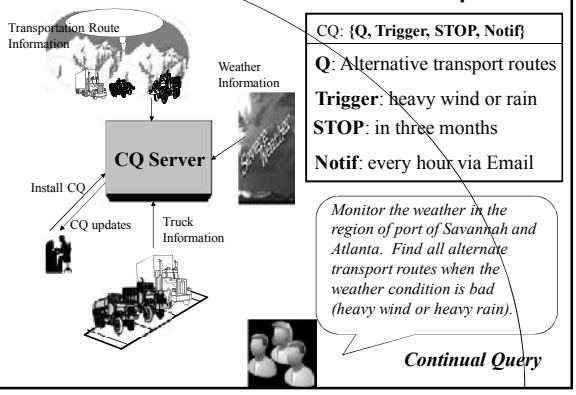


Code Generation & Compilation

Continual Queries Project (96-05)



Continual Queries Concept



CQ: **{Q, Trigger, STOP, Notif}**

Q: Alternative transport routes

Trigger: heavy wind or rain

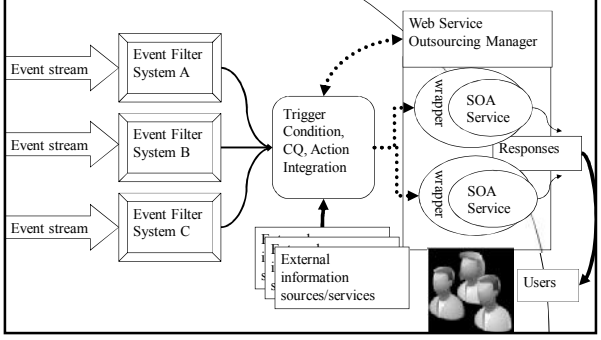
STOP: in three months

Notif: every hour via Email

Monitor the weather in the region of port of Savannah and Atlanta. Find all alternate transport routes when the weather condition is bad (heavy wind or heavy rain).

Continual Query

CQ and SOA Event Services



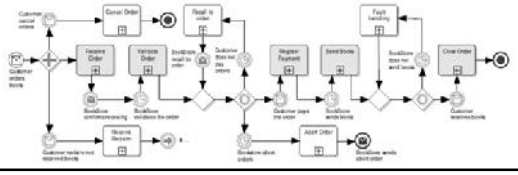
WED-flow Example

- Application example: exception handling
  - Process-oriented exception handling causes serious code bloat
- Simple book ordering application
  - WED-flow approach starts from "happy path" (no exceptions)

61

WED-flow Exception Handling

- Event and state-based (using CQ for control flow)
  - Reuse of recovery actions in backward recovery
  - Reuse of alternative paths in forward recovery



Big Research Challenges

- CPS/IOT will change our lives
- Guaranteed quality of service needed
  - Predictable performance (incl. real-time)
  - High availability (and reliability)
  - High confidence (verifiably correct execution)
  - System and application/data security
  - Privacy protection for personal information while facilitating new functionality

63

Events Will Be Very Useful

- Some CPS projects are extending classic approaches
  - Adaptive control techniques
  - Adaptive learning algorithms
  - However, they are still process-oriented (with problems such as state explosion)
- Let's try "new" ideas and potentially more scalable approaches
  - Examples: events, CQ, and data flow

64

Dynamic V&V Challenge

- Well known limitations of classic (process-oriented) V&V
  - State explosion (including composition)
  - Changes (evolution and adaptation) require re-verification from scratch
- Need "new" ideas and potentially more scalable approaches

65

Security and Privacy Challenges

- Security breaches a fact of life
  - Sony (PlayStation Network), Epsilon (world's largest email marketing service provider), and many more
  - Botnets (order of M nodes)
  - CPS/IOT apps are prime targets
- Privacy vs. functionality trade-offs
  - Example: location-based services, many CPS/ITO apps "need to know"

66

Quality of Information Challenge

- QoI = information analog of QoS
  - Information theory: all bits are equal
  - That's atomic theory (e.g., cannot explain electricity)
- We ***know*** that some bits are good and other bits are bad
  - Spam and deception (email, web, social networks, click fraud, all media, sensors)
- Some progress but not enough (Gates)

67

Performance Challenges

- Cloud: scalable, but unpredictable
  - MapReduce apps scale, but become less predictable (laggards problem)
  - N-Tier apps have both scalability and predictability problems
- Real-time performance for CPS/IOT
  - Initial proponents of CPS are from RT community, but classic RT techniques need not apply

68

Summary

- CPS/IOT offer visionary capabilities
  - Alert on heart attack before it happens
  - Bending space and time
- CPS/IOT will require new (software) technologies
  - Many dimensions of QoS: V&V of an evolving, adaptable system; security and privacy; predictable performance; and more….

69

Conclusion

- IT about to change the world (Again!)
- This vision has many names: CPS, IOT, Smarter Planet, and more
  - Significant technology push (low risk)
  - Great application pull (high return on investment)
- You can play a role in this revolution
  - Software is the bottleneck!
  - Events can be part of the solution….

70