Distributed embedded systems
- characteristics, examples, trends and challenges

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Outline

• Recap – why, what and how of distributed systems
  ▪ Characteristics, Advantages, Problems

• Design issues for distributed embedded systems
  ▪ Systems and application examples
  ▪ Trends and research
What Is A Distributed System?

- A set of nodes connected by the network, cooperating to achieve a common goal
  - Node: a μC +I/O + communication interface
  - One or multiple networks: wired, wireless
Analogy

- Setup phase:
  - Communication model/pattern
  - Physical level; logical level; reliability
  - Broadcast vs. Point-to-point mode

- Design and implementation
  - Functions ~ the phrases
    - Allocated to hardware elements – “nodes”
  - Timing and global clock
  - Access to the same com. network/scheduling
  - Application control logic - centralized

Communication models

<table>
<thead>
<tr>
<th>OSI model oriented</th>
<th>RT model</th>
</tr>
</thead>
<tbody>
<tr>
<td>General purpose</td>
<td>Dedicated</td>
</tr>
<tr>
<td>Little apriori knowledge</td>
<td>Often static</td>
</tr>
<tr>
<td>Point to point logical connection</td>
<td>Multicast</td>
</tr>
<tr>
<td>Sender &amp; receiver addressing</td>
<td>Source addressing</td>
</tr>
<tr>
<td>Positive ack retransmission</td>
<td>Datagram</td>
</tr>
<tr>
<td>E.g. TCP/IP!</td>
<td>E.g. CAN!</td>
</tr>
</tbody>
</table>
Views of distributed systems

- Software allocation and roles of nodes
- Application program view
- Driver view
- Logical topology
- Physical layout
- Cables and wires
- Physical vs. Logical communication
  - Protocols

The mapping problem

Vehicle stability  Suspension  Diagnostics  Driver in the loop

Local control function
Sensor  Actuator

Local control function
Sensor  Actuator

Gateway

Where do data, programs and control go?
Application programmer view

```c
msg[0]=0;
...
msg[6]=0;
msg[7]=50;

CANSendMsg( 0, 0x0cfe6cee, msg, 8, 0 );
delay_ms(1000);
dip204_clear_display();
...
```

Driver view illustrated through Coldfire CAN

Courtesy of Freescale
Logical hardware topology: trains

![Diagram of logical hardware topology for trains, showing nodes, vehicle buses, and train buses.]

Physical layout

![Diagram of physical layout showing sensor module, drop cables, digital I/O module, and trunk cable.]

Courtesy of Bombardier

Courtesy of Kvaser
Signal and cabling view

Data transmission over CAN:
Application, datalink and physical level views

`CANSendMsg( 0, 0x0cfe6cee, msg, 8, 0 );`

And levels inbetween!
- Driver software

Diff. Transmission (Rs422)
Views of distributed systems

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Why distributed systems?

Why not Analog Cabling?

- Traditional method: a μC is connected to distributed sensors and actuators by dedicated analog cables
- An example: 1900 wires, 2.2km long
Reducing Cables with Network

- Digital signals – robustness against noise
  - Increase data integrity
- Reduce the cost of cables, connectors
- Increase system reliability (fewer connectors)
- Shared resources and information:
  - Sensors, actuators, computations, ...
- Modularity
- Performance
- Local intelligence

A Mechatronic Module

- Scania diesel engine and controller

Interfaces:
- Mechanical Connections
- CAN
Many advantages!!!
What are the problems???

- (partial) failures
- Delays
- Consistency
- Organizational challenges
- How to deal with distributed functions?
- How to verify?

Distributed systems
– failure modes

**Nodes**
- Omission
  - Fail-silent
  - Signalled failure
- Value
  - Wrong data sent
- Timing
  - E.g. too early, too late
- Interference
  - “Babbling idiot”
- Commission
  - Unintended message

**Network**
- Omission
  - Transient or permanent
  - Permanent failure – special case: Network becomes partitioned!
- Value
  - Alteration of value
- Timing
  - Network failure causes delay/different delays
- Interference
- Commission

Attributes: Duration, Detectability, Symmetry
Distributed state variables, \{M1, M2, M3\} => the system state; is it consistent?

When is the state required to be consistent?
Consistency in the presence of faults?
Trade-offs --> compare voice vs. file transfer!

Time delays in distributed systems

Sending Node
Application
Access Control
Comm. Interf.

Receiving Node
Application
Access Control
Comm. Interf.

preparation, send
decode, retrieve
wait
transmission
Delays and event ordering

- Incorrect event order possible

![Diagram of delays and event ordering]

Clock synchronization

Local unsynchronized clocks:
- Granularity
- Drift rate, e.g. $10^{-7}s/s$
- Clock drift rate ~ temp. & voltage applied to the crystal resonator

Free running clocks will drift apart

Clock synchronization
- Establishing an approximate global time within a system
- Internal clock synchronization -> precision of the global clock
  → Master/slave vs. distributed clock synchronization
- Synchronization to an external time reference
Why are there so many types of networks, technologies and protocols??

Controller area network
CanOpen, Volcano, J1939, ...
LIN, Most, Flexray
Train Communication Network

MIL1553B

Wireless, short range
Cellular

Ethernet, TCP/IP

BACnet, Lonworks

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Design issues

• Centralized or distributed system?
• Which type of distributed system?
  ▪ Logical topology and physical layout
  ▪ Decentralization of data, programs & control
  ▪ Which communication protocol
• How to design and dimension them?
  ▪ The importance of the system architecture!
    → Cost vs. Reliability vs. Performance vs. ...
  ▪ Delays, synchronization and failures
  ▪ Verification?
  ▪ Who does what?

Distributed I/O

• Common in process control
• Additional time-delay in control loop
• Care has to be taken to synchronize sensor inputs and multiple outputs
Decentralized local control

- Common in machine control and automotive
- Need for synchronization of level 1 loops with coordinator

Level 2
- Set-points and Coordination
- Network

Level 1
- Feedback Ctrl
- Output
- Input

Common in machine control and automotive
Need for synchronization of level 1 loops with coordinator

Attitude control system in the science mode of operation

From rate sensors
Reaction wheel speed

Hydrazine thruster

Smart-1 dynamics

Planetary system and Smart-1 kinematics

Rate

Star tracker

Sun

Sensors

Target attitude
Estimated attitude

Mode logic

Controller

Estimation

Reactive wheels

Smart-1 dynamics

Planetary system and Smart-1 kinematics

Rate

Star tracker

Sun

Sensors
Smart-1 block diagram

• One of a kind!
• Robustness & fault tolerance
• Space environment: radiation
• Autonomy
• Power
• Mission critical
• Real-time, slow time constants

Main on-board computer

TCS695E single chip ERC32 processor, 20 MHz clock
EEPROM 2 Mbyte EDAC protected
SRAM 3 Mbytes EDAC protected, needs SW scrubbing cycle < 1 minute,
MassMemory 512 Mbyte, EDAC protected, HW scrubbing

CAN controllers, 2 kBytes FIFO in reception path
→ Purchased VHDL code; radiation tolerant FPGA

Watchdog, 2 s timeout, can be disabled per pulse telecommand
JTAG I/F for EEPROM software upload and board HW checkout
Example application: stability control

- Vehicle speed
- Vehicle slip angle
- Vehicle yaw rate

Source: ESC education - www.esceducation.org

Example application: vehicle stability control

Disturbances

Driver

- Yaw/slip controller
- Brake controller
- Engine controller

Wheel dynamics

Engine dynamics

Vehicle dynamics

Controller area network and vehicle computers

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Embedded systems course, MF2042
A view of a modern car

Which nodes are involved in vehicle stability control?

Distributed systems perspective

- 70’s – Distributed control in process automation
- 80’s – Avionics
- 90’s – Automotive
- External connectivity and wireless

Telecom; cellular telephony
Computer communication; Internet; TCP/IP, wireless
Short range wireless communication; Bluetooth, Zigbee, …
Trends

- Connectivity
- New (distributed) functions
- Convergence
- Standardized platforms
  - Middleware – for example Autosar
  - Protocols
- Product lines and model-based development
  - Reuse of SW and HW components
- Evolving electronics; multicore
Autosar – Automotive SW architecture

Autosar also defines information exchange

Benefits of wireless networking in industrial control

- Cost (wiring and installation)
- Flexibility
  - Less physical design limitations
  - More mobile equipment
  - Faster commissioning and reconfiguration
- Reliability
  - No cable wear and tear
  - No connector failure

Courtesy of Karl-Henrik Johansson
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**Barriers** against wireless networking in industrial control


**Prototyping and different hardware**

![Diagram showing controller and controlled system connections]
Hardware in the loop simulation

Concept – for a network test
Summary

- Why, what & how of distributed systems
  - Remember the exercise!

- Design issues for distributed embedded systems
  - Architecture and verification
  - Dealing with complexity
  - Trends:
    - Increasing connectivity and convergence
    - Standardization