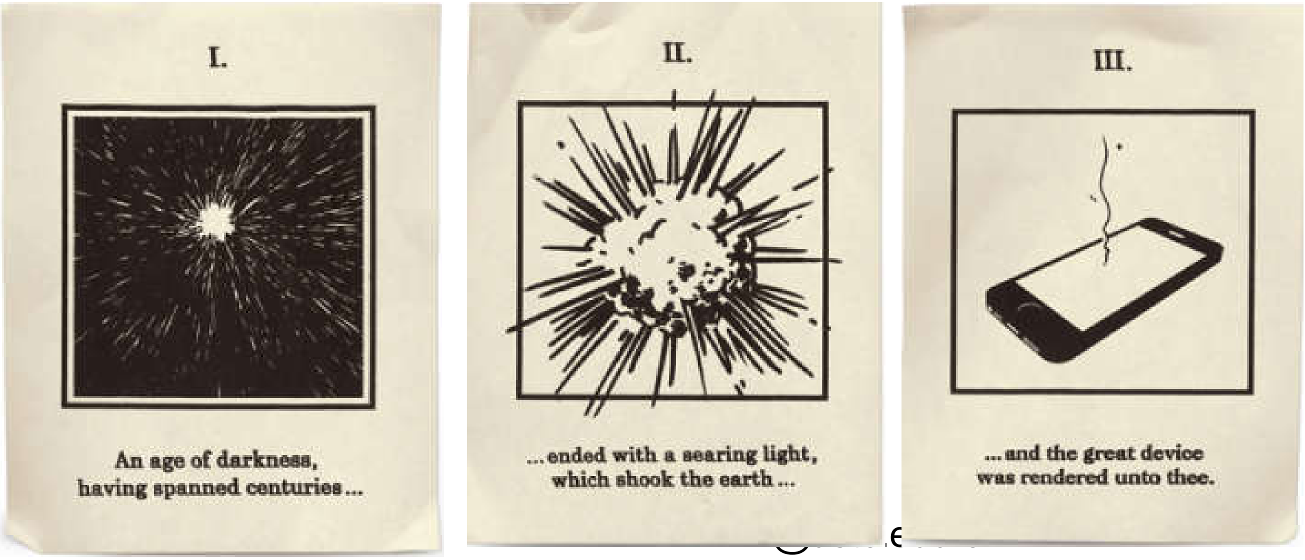
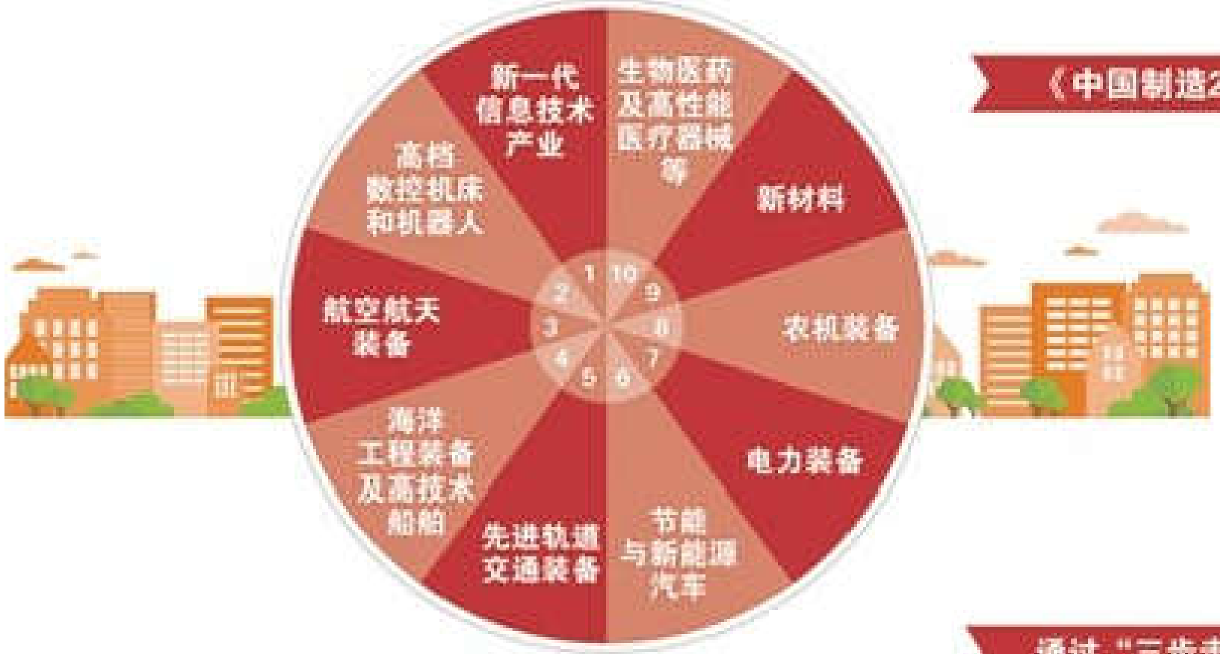
美国进口一部“中国产”iPhone

- 总价＝$179
  - 日本34%：闪存＝$24，屏幕＝$35
  - 德国17%：GPS＋摄像＋WiFi＝$30
  - 南韩13%：处理器＋零部件＝$23
  - 米国6%：蓝牙＋录音＋3G＝$12
  - 其他：材料＋软件许可＋专利＝$48
  - 中国3.6%：组装＝$6.5

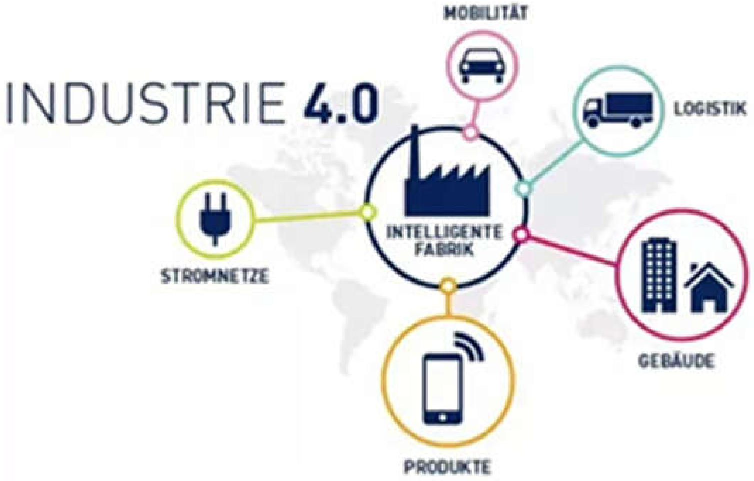

I.
An age of darkness,
having spanned centuries...
II.
...ended with a searing light,
which shook the earth...
III.
...and the great device
was rendered unto thee.

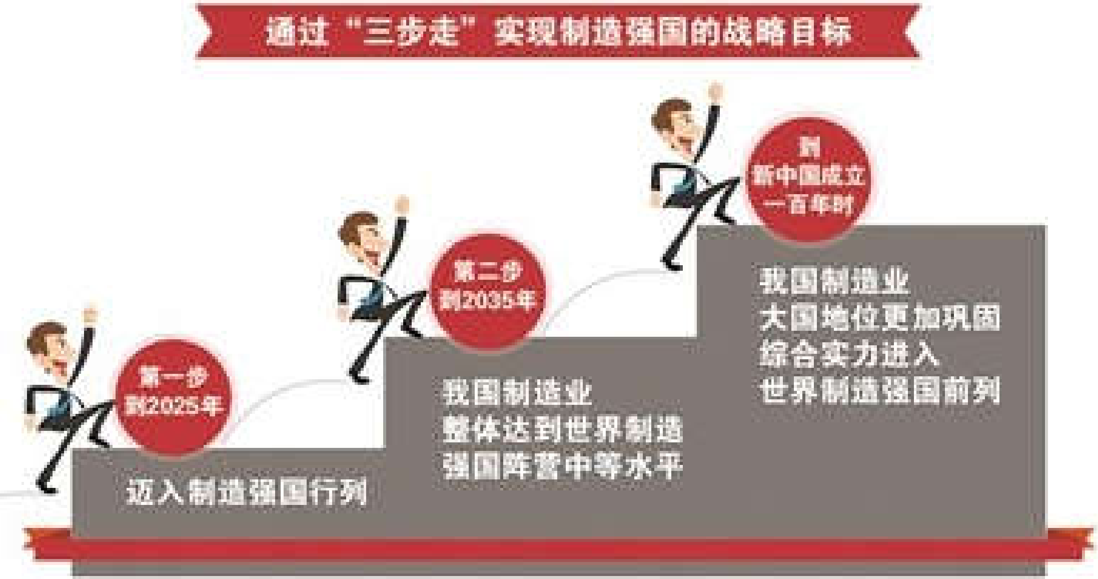
《中国制造2025》计划

《中国制造2025》明确了十大重点领域


新一代信息技术产业
生物医药及高性能医疗器械等
新材料
农机装备
电力装备
节能与新能源汽车
先进轨道交通装备
海洋工程装备及高技术船舶
航空航天装备
高档数控机床和机器人
1
2
3
4
5
6
7
8
9
10

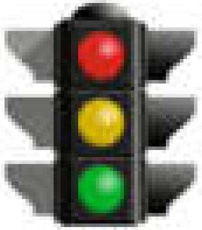
2015年5月8日
国务院印发


INDUSTRIE 4.0
MOBILITÄT
LOGISTIK
INTELLIGENTE FABRIK
STROMNETZE
GEBÄUDE
PRODUKTE


通过"三步走"实现制造强国的战略目标
第一步 到2025年
迈入制造强国行列
第二步 到2035年
我国制造业整体达到世界制造强国阵营中等水平
到 新中国成立一百年时
我国制造业大国地位更加巩固 综合实力进入世界制造强国前列

Embedded Systems around us

Fax Machine

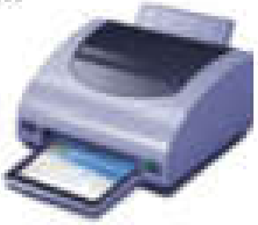


Traffic Management

Security System

Television

Aircraft Flight Control

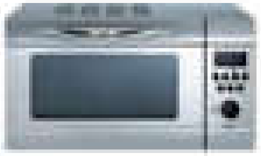


Printer

Audio System

Ultra Sound Machine

Camera



Microwave Oven

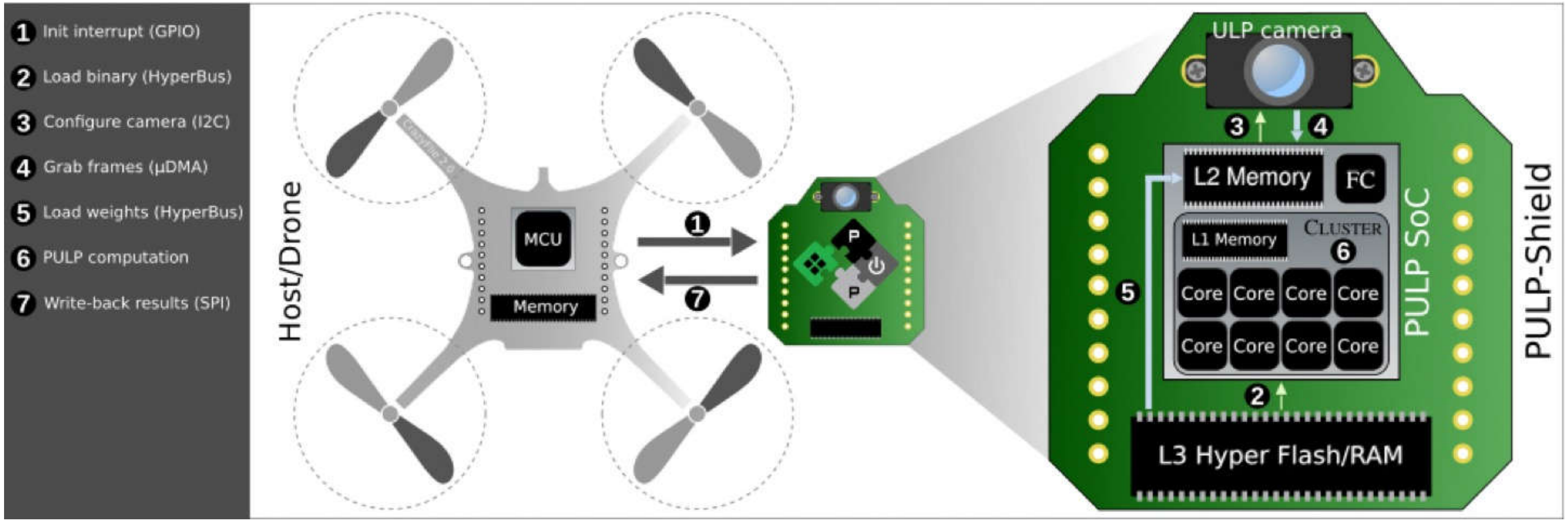
CPS Example – Printing Press

Bosch-Rexroth

- *High-speed, high precision*
  - *Speed: 1 inch/ms*
  - *Precision: 0.01 inch*

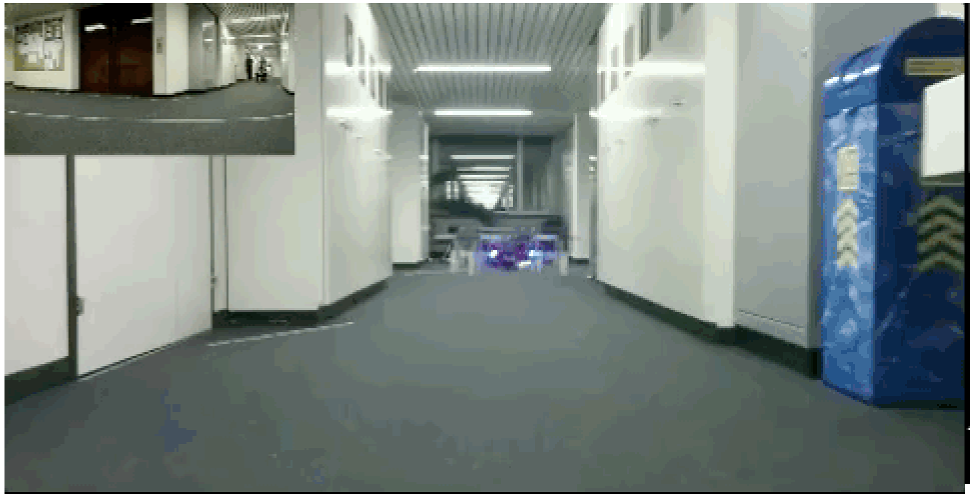
    -> Time accuracy: 10us
- *Open standards (Ethernet)*
  - *Synchronous, Time-Triggered*
  - *IEEE 1588 time-sync protocol*
- *Application aspects*
  - *local (control)*
  - *distributed (coordination)*
  - *global (modes)*

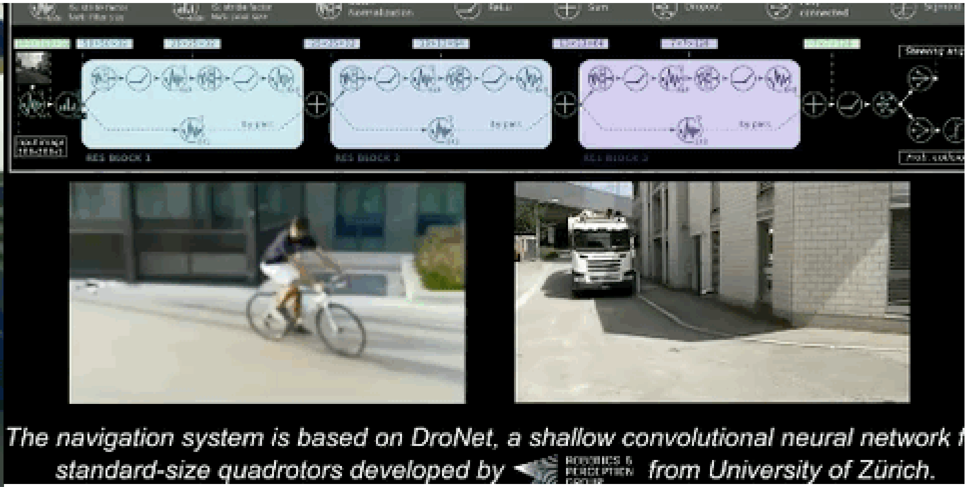
嵌入式智能系统：纳米级无人机，仅重27克 CNN自主导航，史上最小@ETH Zurich



1. Init interrupt (GPIO)
2. Load binary (HyperBus)
3. Configure camera (I2C)
4. Grab frames (µDMA)
5. Load weights (HyperBus)
6. PULP computation
7. Write-back results (SPI)

Host/Drone
Crazyflie 2.0
MCU
Memory
1
7
P
P
ULP camera
3
4
L2 Memory
FC
L1 Memory
Cluster
6
5
Core
Core
Core
Core
Core
Core
Core
Core
2
L3 Hyper Flash/RAM
PULP SoC
PULP-Shield





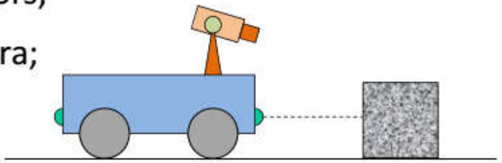
RES BLOCK 1
RES BLOCK 2
RES BLOCK 3
Steering angle
Prob. collision

The navigation system is based on DroNet, a shallow convolutional neural network f standard-size quadrotors developed by ROBOTICS & PERCEPTION GROUP from University of Zürich.

A robot control example

Consider a mobile robot equipped with:

- two actuated wheels;
- two proximity (US) sensors;
- a mobile (pan/tilt) camera;
- a wireless tranceiver.



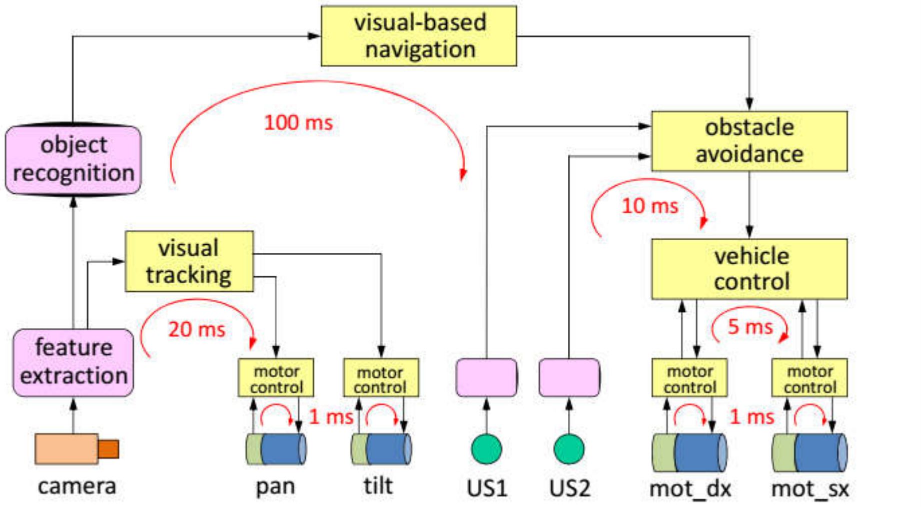
Goal

- Follow a path based on visual feedback;
- Avoid obstacles;
- Send complete robot status every 20 ms.

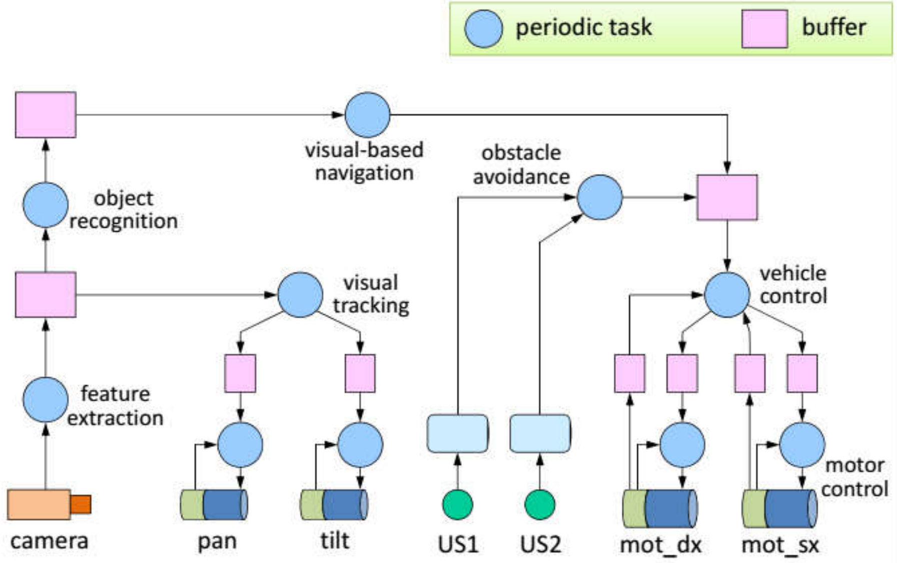
Design requirements

- **Modularity**: a subsystem must be developed without knowing the details of other subsystems (team work).
- **Configurability**: software must be adapted to different situations (through the use of suitable parameters) without changing the source code.
- **Portability**: minimize code changes when porting the system to different hardware platforms.
- **Predictability**: allow the estimation of maximum delays.
- **Efficiency**: optimize the use of available resources (computation time, memory, energy).

Hierarchical control


visual-based navigation
100 ms
object recognition
obstacle avoidance
10 ms
vehicle control
visual tracking
20 ms
5 ms
feature extraction
motor control
motor control
motor control
motor control
1 ms
1 ms
camera
pan
tilt
US1
US2
mot_dx
mot_sx

Software View


periodic task
buffer
visual-based navigation
obstacle avoidance
object recognition
vehicle control
visual tracking
feature extraction
motor control
camera
pan
tilt
US1
US2
mot_dx
mot_sx

计算模型：Turning Machine

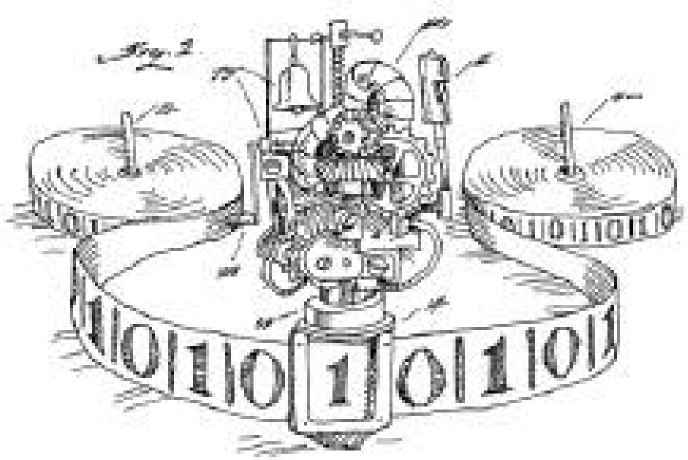
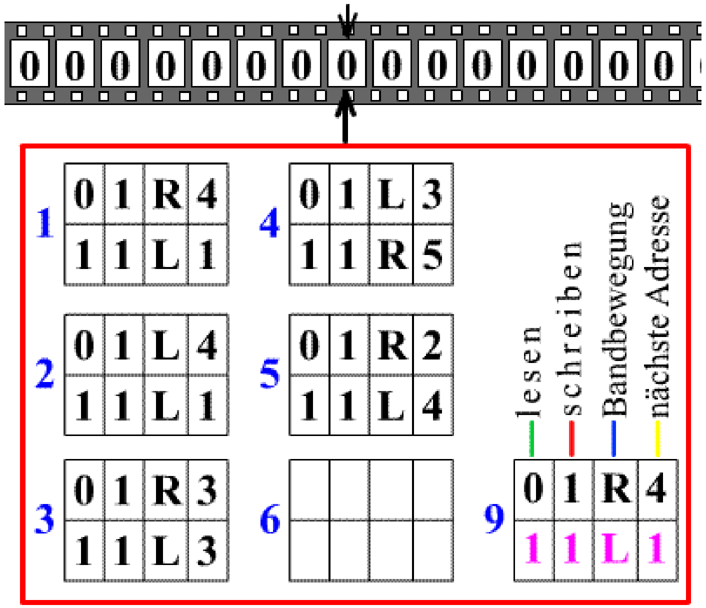
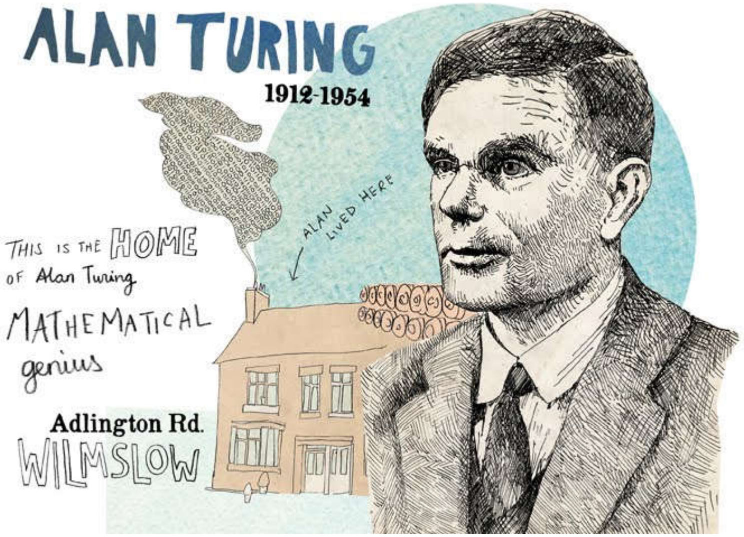


Fig. 2
1 1 0 1 1 0 1 0 1 1 0 1


0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
1
0 1 R 4
1 1 L 1
2
0 1 L 4
1 1 L 1
3
0 1 R 3
1 1 L 3
4
0 1 L 3
1 1 R 5
5
0 1 R 2
1 1 L 4
6
9
lesen
schreiben
Bandbewegung
nächste Adresse
0 1 R 4
1 1 L 1


ALAN TURING
1912-1954
THIS IS THE HOME OF Alan Turing
MATHEMATICAL genius
Adlington Rd.
WILMSLOW
ALAN LIVED HERE

- 变迁系统
  - Timing：逻辑步？
- 计算复杂性问题
  - 时间复杂度
    - Time：metrics

The Real-Time Problem：缺乏时间语义！

- Programming languages have no time in their core semantics
- Temporal properties are viewed as “non-functional”
- Precise timing is poorly supported by hardware architectures
- Operating systems provide timed behavior on a best-effort basis (e.g. using priorities).
- Priorities are widely misused in practice

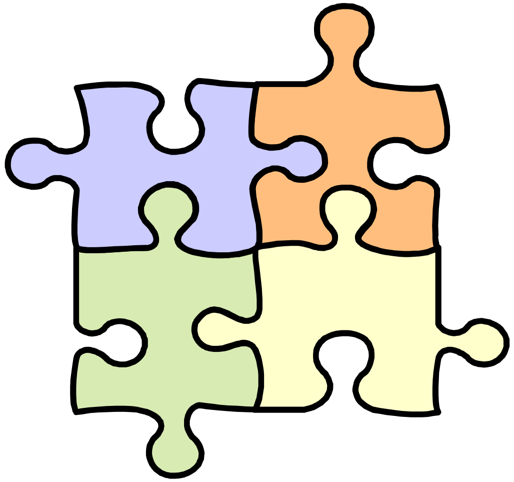
嵌入式实时系统设计方法

Embedded Computing
Real-Time Computing
Embedded Real-Time Systems

李曦 llxx@ustc.edu.cn
陈香兰 xlanchen@ustc.edu.cn

Presentation Outline

- 嵌入式系统概述
  - 嵌入式系统的定义
  - 嵌入式系统的特征与指标
  - 嵌入式系统分类
- 发展方向：CPS
- 热点应用示例
  - 汽车电子
  - 。。。
- 课程说明



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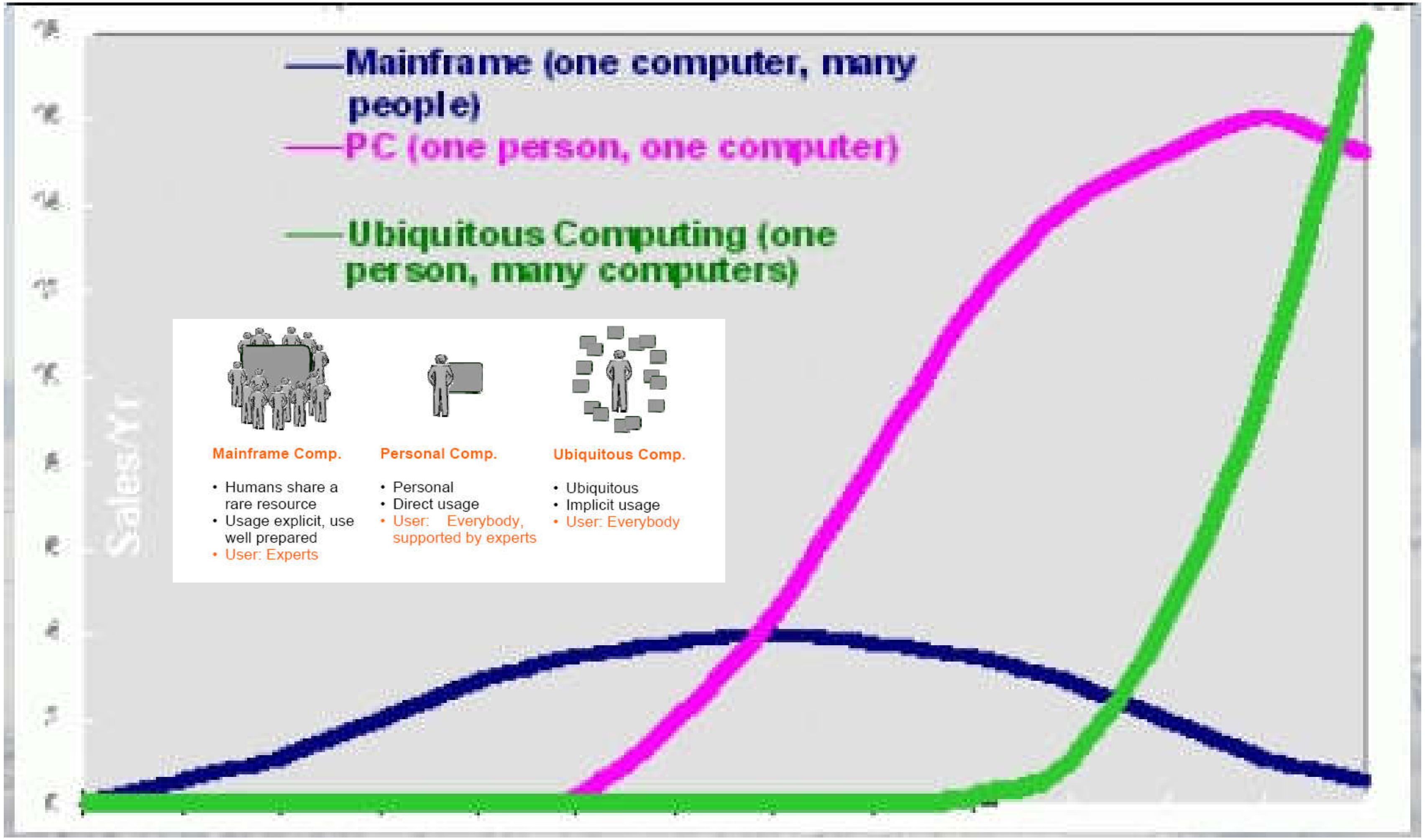
计算机系统的发展趋势



Mainframe Comp.

- Humans share a rare resource
- Usage explicit, use well prepared
- User: Experts

Personal Comp.

- Personal
- Direct usage
- User: Everybody, supported by experts

Ubiquitous Comp.

- Ubiquitous
- Implicit usage
- User: Everybody

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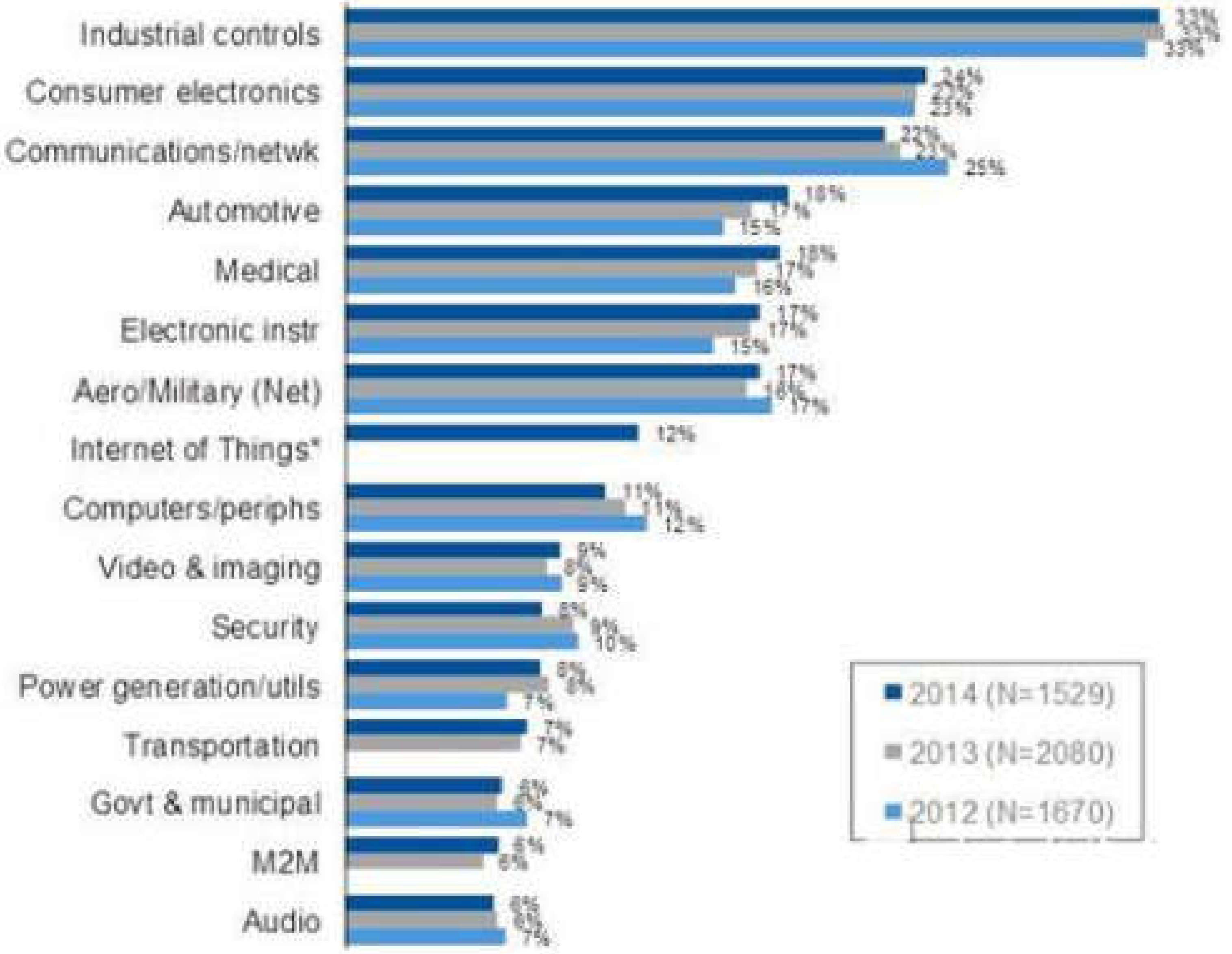
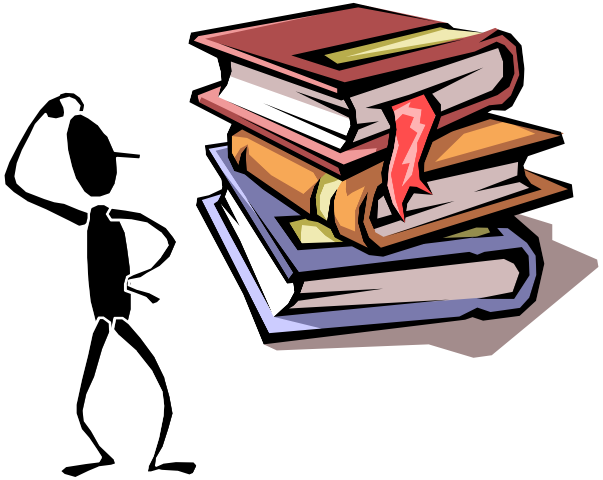
嵌入式系统应用领域


Industrial controls
33%
33%
33%
Consumer electronics
24%
23%
23%
Communications/netwk
22%
23%
25%
Automotive
18%
17%
15%
Medical
18%
17%
16%
Electronic instr
17%
17%
15%
Aero/Military (Net)
17%
16%
17%
Internet of Things*
12%
Computers/periphs
11%
11%
12%
Video & imaging
9%
8%
9%
Security
8%
9%
10%
Power generation/utils
8%
8%
7%
Transportation
7%
7%
Govt & municipal
6%
6%
7%
M2M
6%
6%
Audio
6%
6%
7%
■ 2014 (N=1529)
■ 2013 (N=2080)
■ 2012 (N=1670)

What is an Embedded System?

- **Embed**
  - Longman Dictionary：***to fix (something) firmly and deeply***
  - Webser Dictionary：***to enclose closely in a surrounding mass***
- **System**
  - implicitly a ***controlling*** system.



嵌入式计算机系统定义

- 以应用为中心、以计算机技术为基础、软件硬件可裁剪、适应应用系统对功能、可靠性、成本、体积、功耗严格要求的专用计算机系统。
  - 量身定做
  - 资源有限
  - “在过去的20年中，虽然嵌入式系统仍是许多消费电子设备、工业设备和军方设备中不可见的部分，但它作为一个整体已经脱颖而出。如今，嵌入式计算不再限于简单设备控制，它已经能以高实时处理率和低能耗来执行复杂的处理任务”。
- Wayne Wolf：《Computers as Components》

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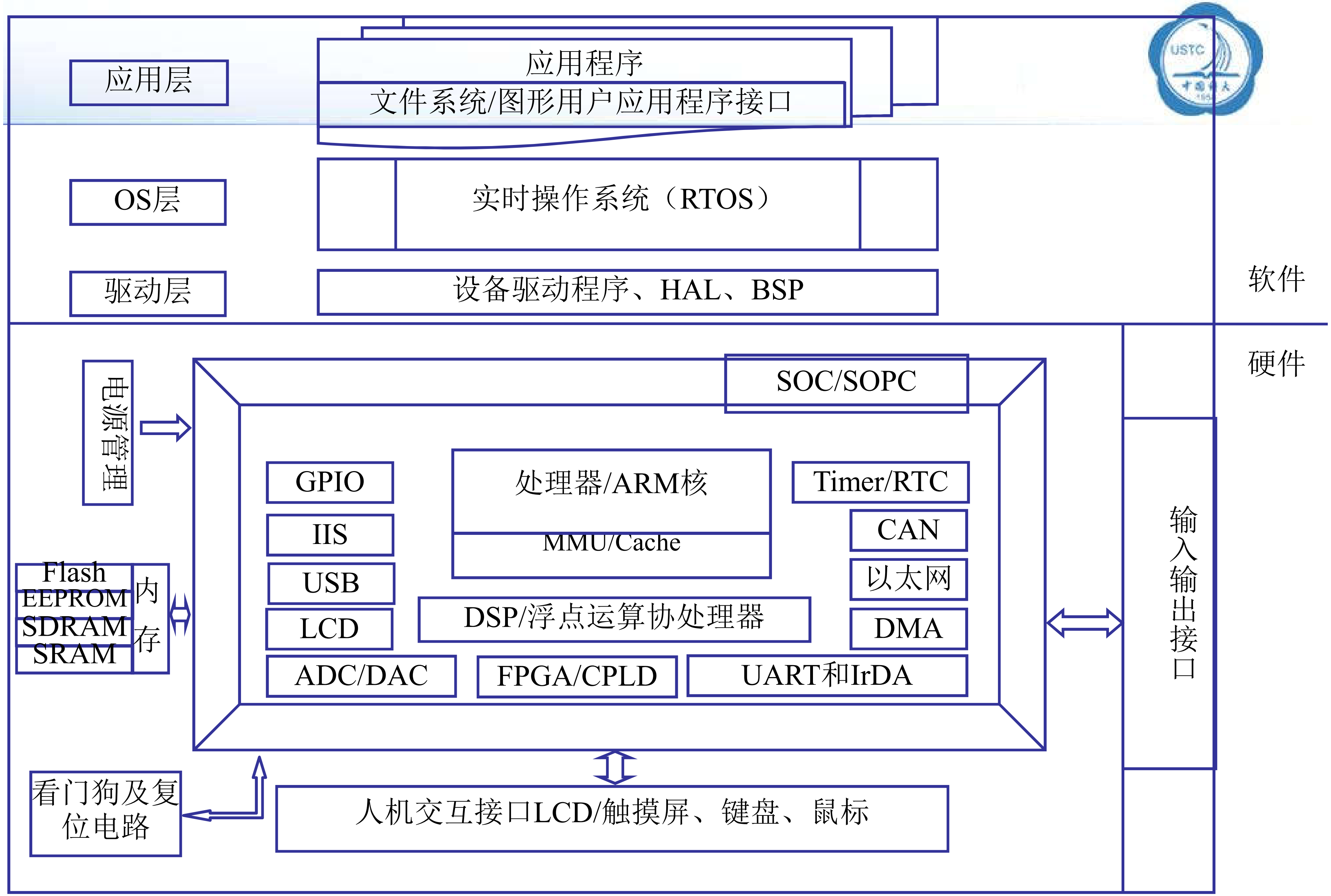

应用层

应用程序

文件系统/图形用户应用程序接口

OS层

实时操作系统（RTOS）

驱动层

设备驱动程序、HAL、BSP

软件

硬件

电源管理

SOC/SOPC

GPIO

IIS

USB

LCD

ADC/DAC

处理器/ARM核

MMU/Cache

DSP/浮点运算协处理器

FPGA/CPLD

UART和IrDA

Timer/RTC

CAN

以太网

DMA

Flash

EEPROM

SDRAM

SRAM

内存

输入输出接口

看门狗及复位电路

人机交互接口LCD/触摸屏、键盘、鼠标

嵌入式计算机系统的组成结构

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Characteristics

- Application and Domain Specific
- Reactive and Real-time
- Distributed
- Heterogeneous
- Operate in harsh environments
- Must meet high-integrity quality attribute requirements
- Small Size and Weight
- Power concerns

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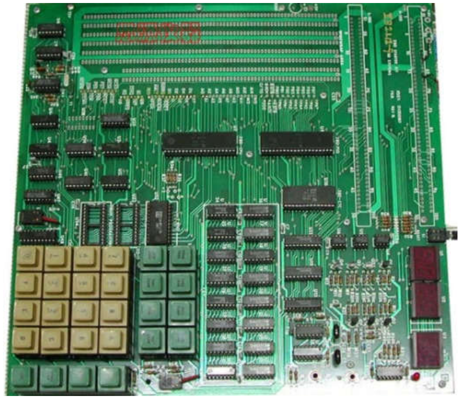
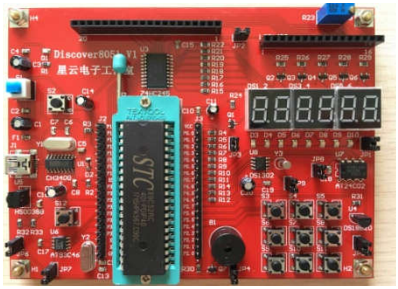
嵌入式计算机系统的形态？

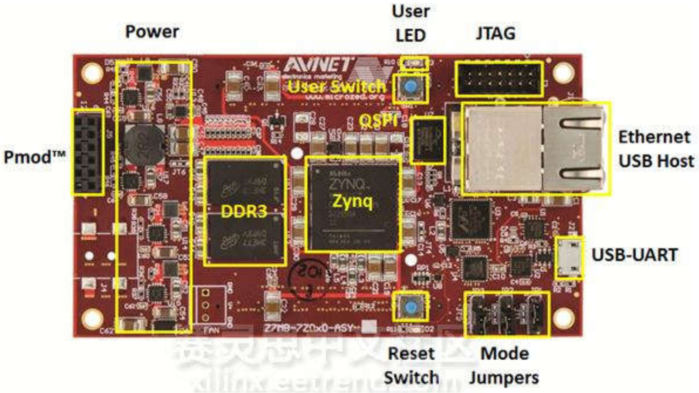
- 单板机Single Board computer
  - Z80



- 单片机Single Chip computer
  - 8051：CPU+片上存储+I/O控制(INT/DMA)+GPIO



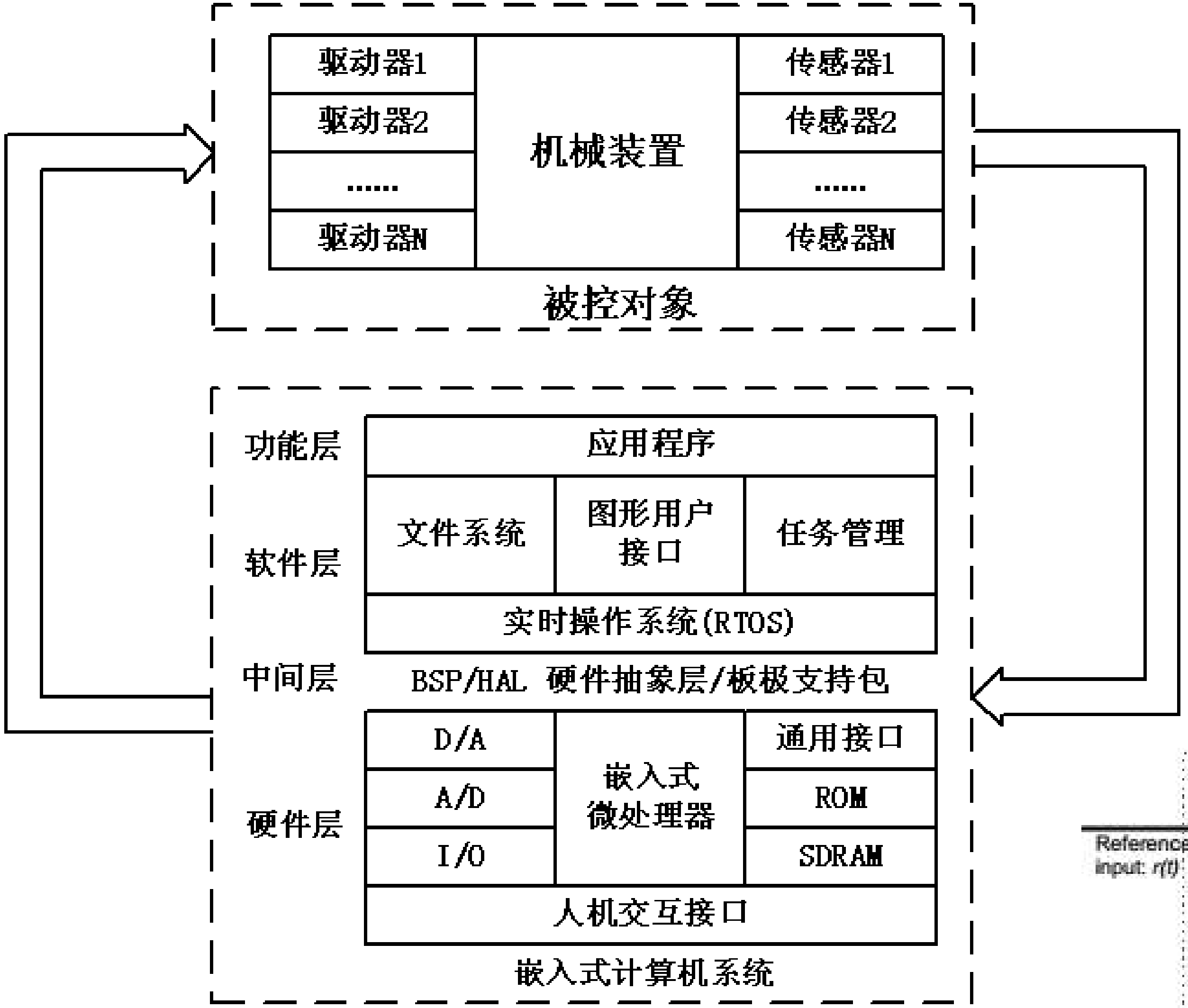
- SOC/SOPC
  - System-on-a-Programmable-Chip
  - Xilinx Zynq系列
    - GPP+DSP+FPGA+片上存储+I/O
  - 调试
  - 可编程、可裁减、可扩充、可升级


Power
User LED
JTAG
User Switch
QSPI
Ethernet USB Host
Pmod™
DDR3
Zynq
USB-UART
Reset Switch
Mode Jumpers

嵌入式控制系统的定义

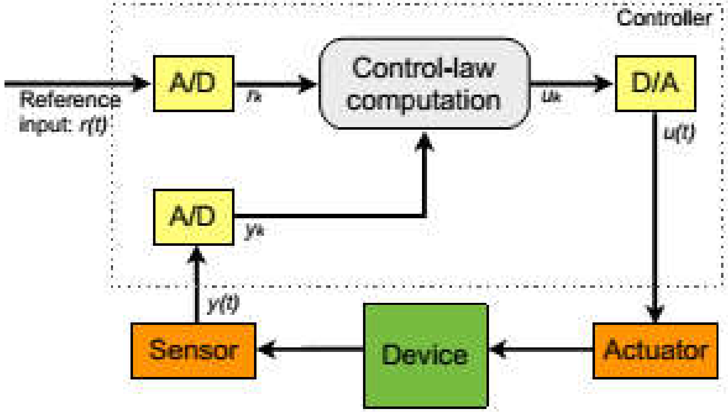
- 早期的典型应用领域在制造业
  - 1962年，美国一个乙烯厂实现工业装置中的直接数字化控制（DDC）
- 英国电机工程师协会
  - “devices used to control, monitor, or assist the operation of equipment, machinery or plants”

嵌入式控制系统的软/硬件框架



驱动器1
驱动器2
……
驱动器N
机械装置
传感器1
传感器2
……
传感器N
被控对象

功能层
应用程序
软件层
文件系统
图形用户接口
任务管理
实时操作系统(RTOS)
中间层
BSP/HAL 硬件抽象层/板极支持包
硬件层
D/A
A/D
I/O
嵌入式微处理器
通用接口
ROM
SDRAM
人机交互接口
嵌入式计算机系统

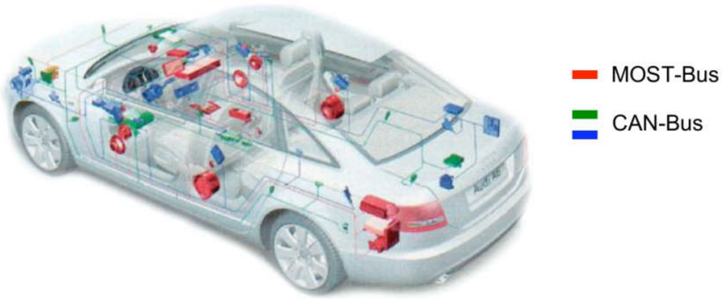

Controller
Reference input: $r(t)$
A/D
r_k
Control-law computation
u_k
D/A
$u(t)$
A/D
y_k
$y(t)$
Sensor
Device
Actuator

Typical ES Functional Requirements

- Control laws
  - e.g. PID control, fuzzy control
- Sequencing control
  - e.g. FSMs, mode changes, switching between control laws
- Signal processing
  - e.g. voice, video
- Fault response
  - e.g. detection, reconfiguration
- Application-specific user interface device
  - e.g. buttons, bells, lights

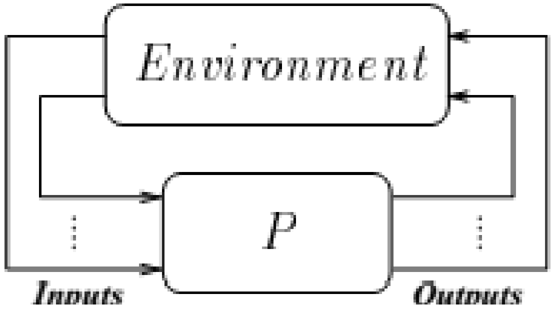
嵌入式系统分类：应用和系统特征

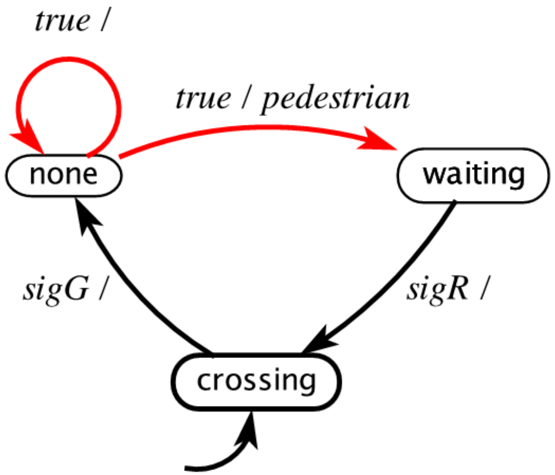
- 按应用领域
  - 消费电子：信息家电、移动终端
    - best-effort service
  - 流处理系统*Streaming app*：通信产品
    - Signal processing system：audio，video
    - 实时交易
  - 控制系统：Instrumentation & Control systems
    - 工业控制
      - 反应式系统
      - 网络控制系统NCS
    - 汽车电子、航空航天
      - 安全关键系统：Safety Critical，MCS
- 按系统特征
  - 反应式系统
  - 实时嵌入式系统
  - 网络控制系统NCS：DRT
  - 容错系统

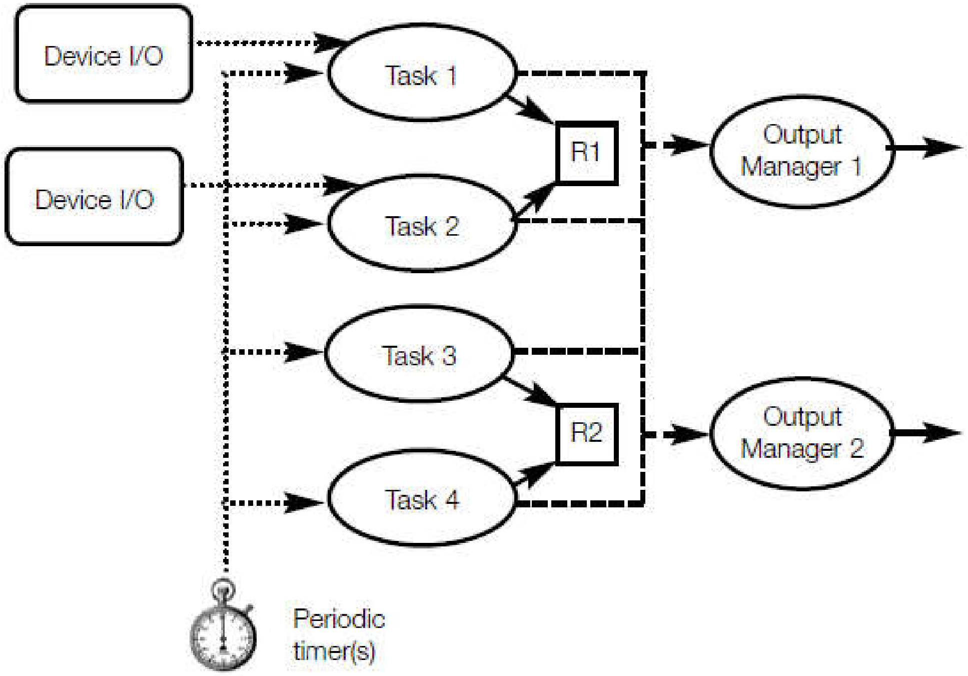


反应式系统：激励/响应系统

- 其行为由一个激励序列和相应的响应动作及时间约束定义
  - 需要在环境限定的时间间隔里对来自环境的激励做出反映
    - “时刻准备着”、“按环境的步调”
  - “输入—计算—输出”：State Transitions
    - 持续不断地响应外部事件，进行状态转移
    - 由一组并发协作的实时任务实现
- 事件驱动系统（控制驱动、中断驱动）
  - 事件-状态-动作

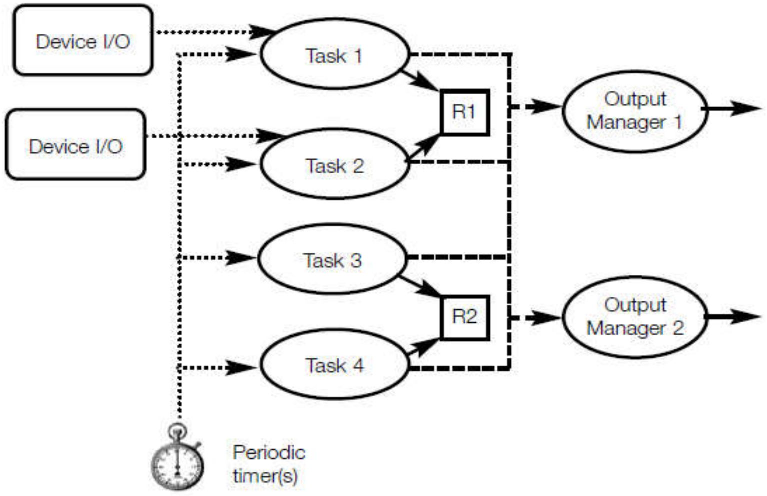

Environment
P
Inputs
Outputs


true /
true / pedestrian
none
waiting
sigG /
sigR /
crossing

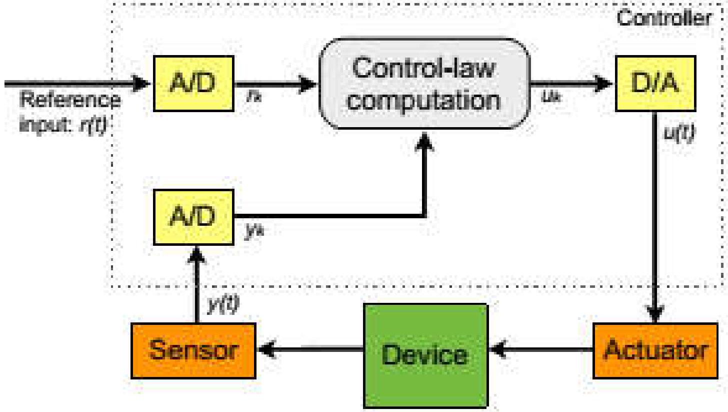

Device I/O
Device I/O
Task 1
Task 2
Task 3
Task 4
R1
R2
Output Manager 1
Output Manager 2
Periodic timer(s)

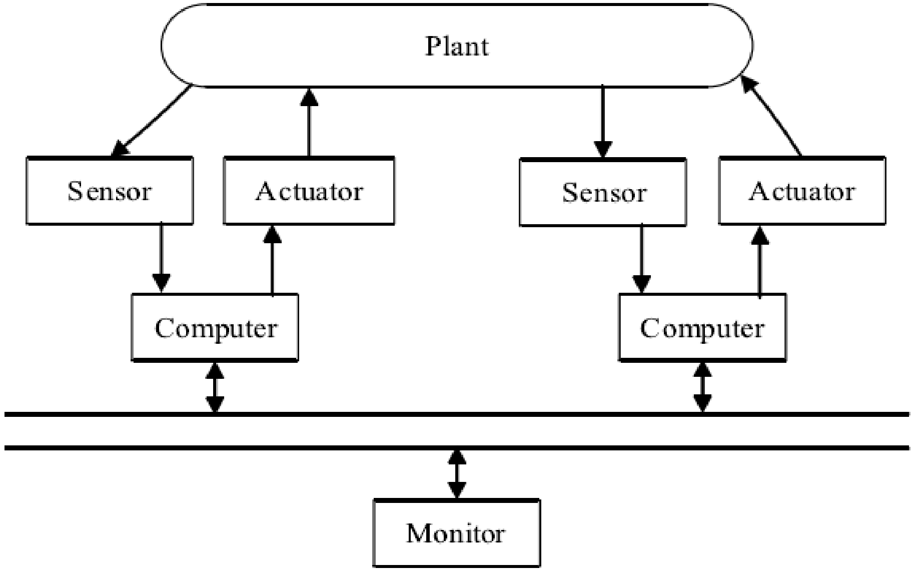
反应式系统的特征

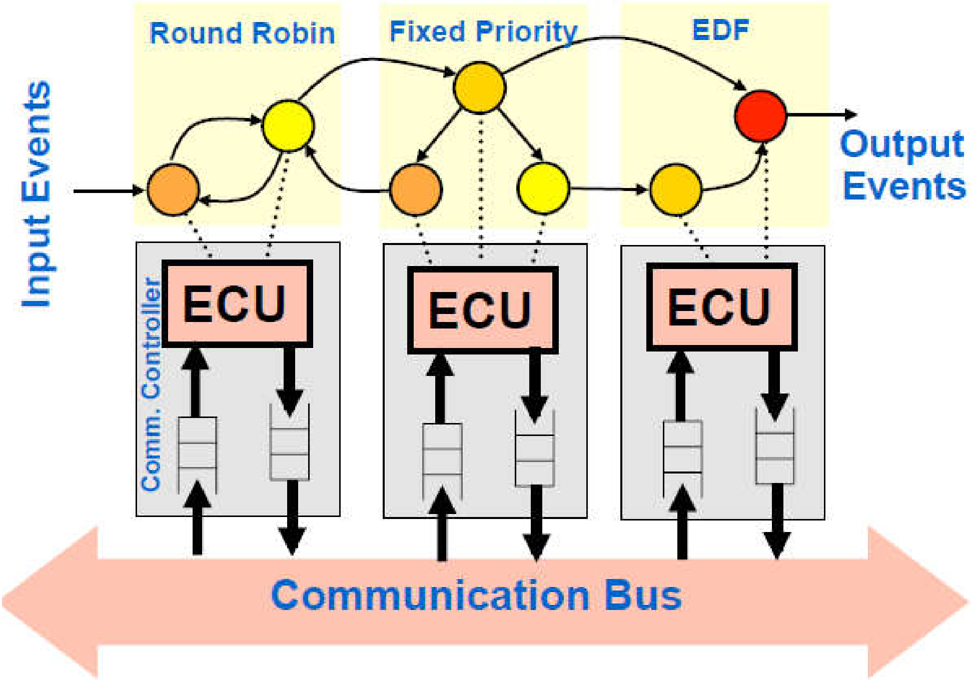
- State Transitions：Intrinsically state-based
  - 持续不断地响应外部事件，进行状态转移
- Real-Time：Task request with **deadlines**
  - Failure to meet deadlines might create safety issues or simply unhappy customers
    - Elevator on a sky-scrapper at 7:45am or 4:55pm
    - Missile flying at low altitude over a mountainous area
- Exceptions：Must handle **unusual** events
  - Interrupt handling is crucial
    - A user blocking an elevator door
    - power blackout
    - memory failure
- Concurrency
  - Task-level
  - Statement-level


Device I/O
Device I/O
Task 1
Task 2
Task 3
Task 4
R1
R2
Output Manager 1
Output Manager 2
Periodic timer(s)

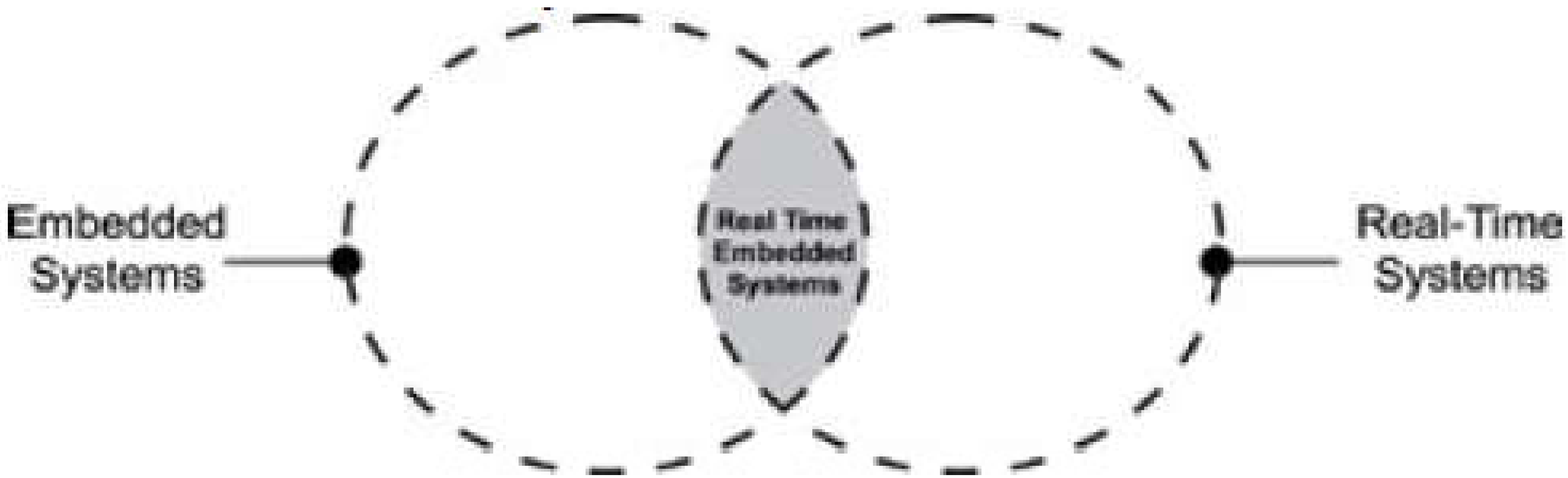
网络控制系统NCS

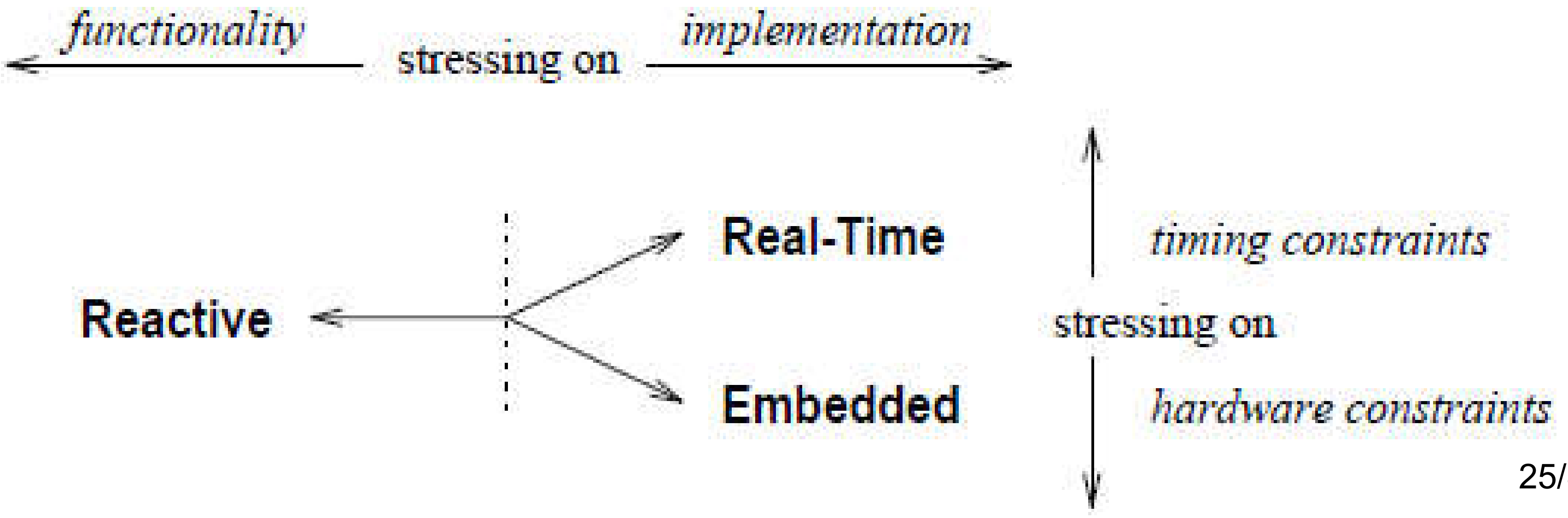

Controller
Reference input: r(t)
A/D
rk
Control-law computation
uk
D/A
u(t)
A/D
yk
y(t)
Sensor
Device
Actuator


Plant
Sensor
Actuator
Sensor
Actuator
Computer
Computer
Monitor


Round Robin
Fixed Priority
EDF
Input Events
Output Events
Comm. Controller
ECU
ECU
ECU
Communication Bus

实时嵌入式系统RTES


Embedded Systems
Real Time Embedded Systems
Real-Time Systems



functionality stressing on *implementation*

Reactive

Real-Time

Embedded

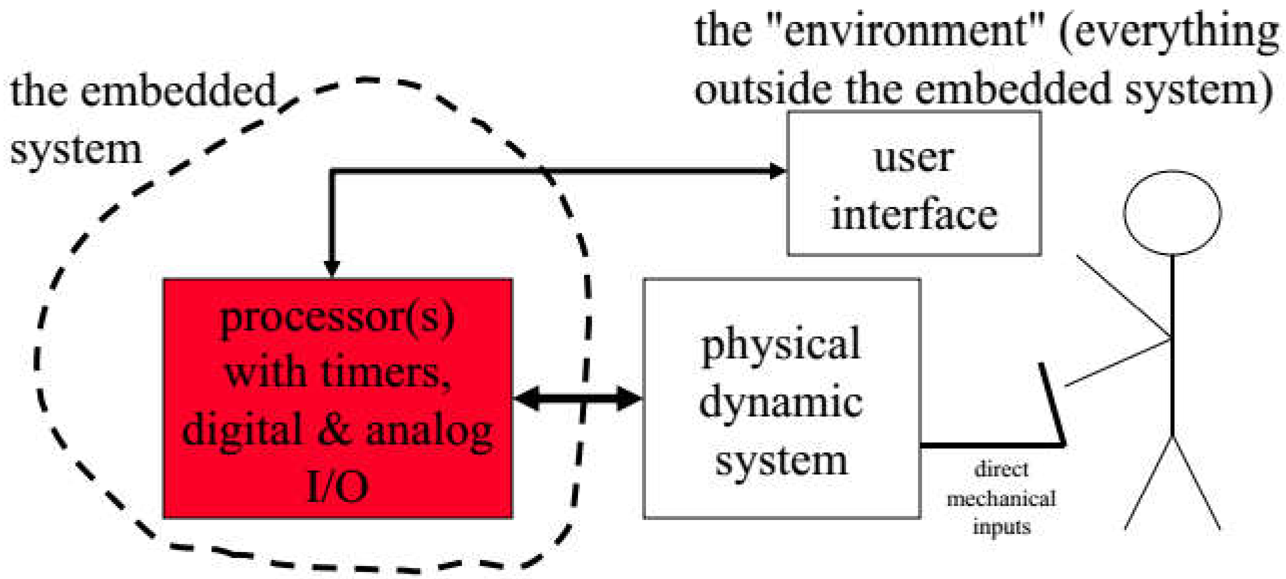
timing constraints

stressing on

hardware constraints

What's "Real" in Real-Time Emb Sys?

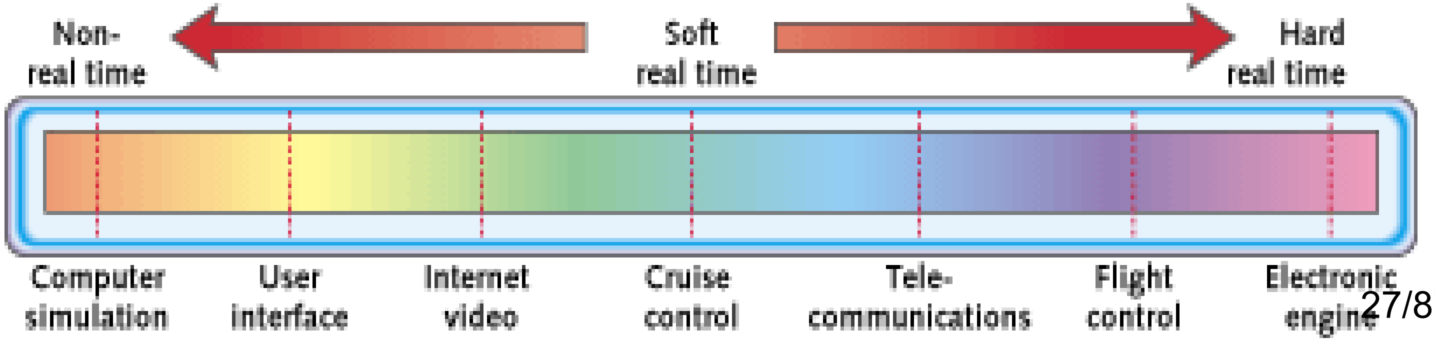
- The (real) environment determines the constraints on:
  - sampling rates
  - computation time
  - jitter (random variations in timing)


the embedded system
the "environment" (everything outside the embedded system)
user interface
processor(s) with timers, digital & analog I/O
physical dynamic system
direct mechanical inputs

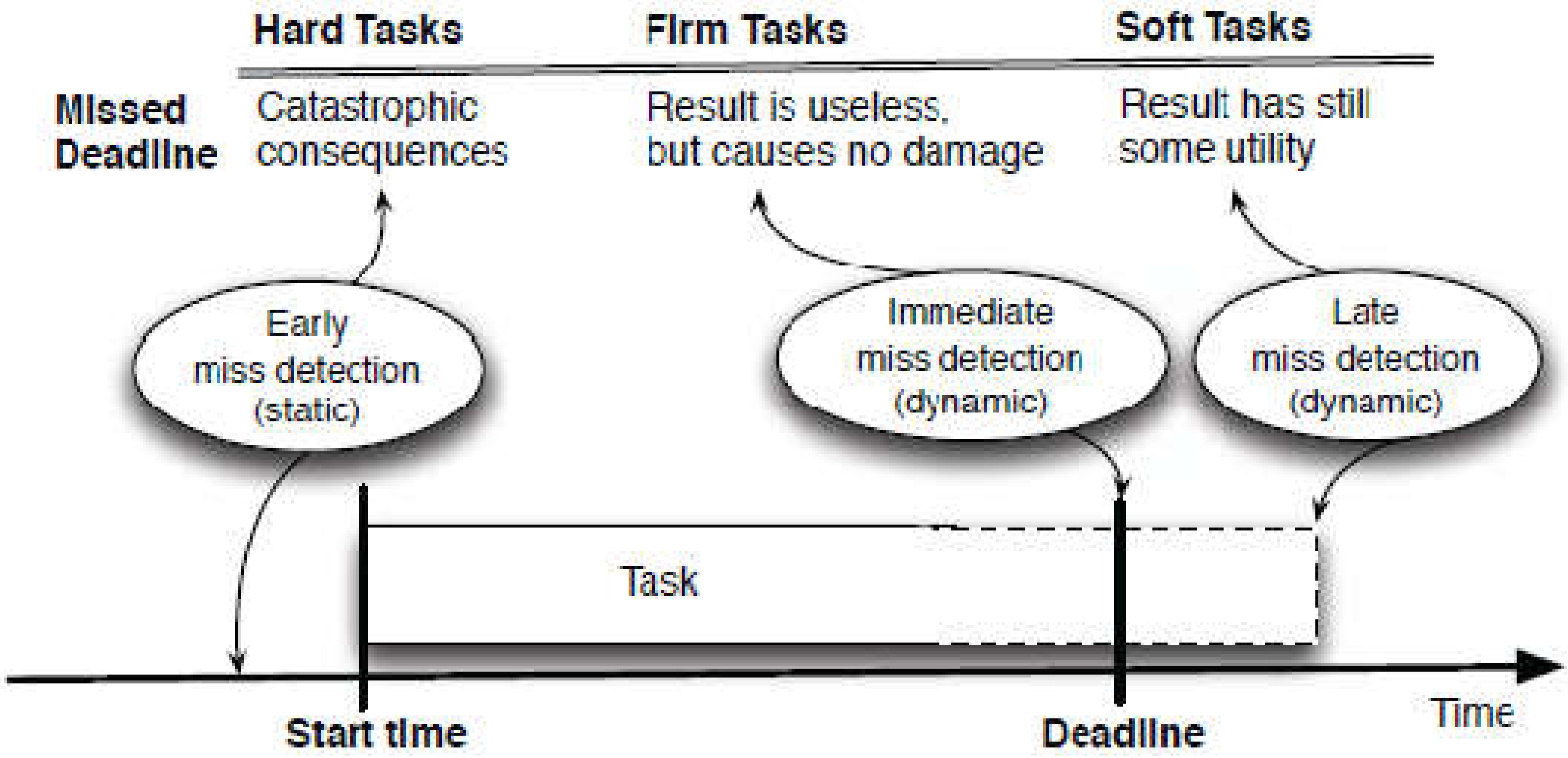
嵌入式系统分类：实时性

- 实时=及时+按时
  - 非实时嵌入式系统
  - 实时嵌入式系统
    - “一个实时系统是指计算的正确性不仅取决于程序的逻辑正确性，也取决于结果产生的时间”
      - Donald Gillies，1991，广泛引用
    - 硬实时系统（工业和军工系统）
      - 安全关键Safety Critical
    - 软实时系统（消费类产品）

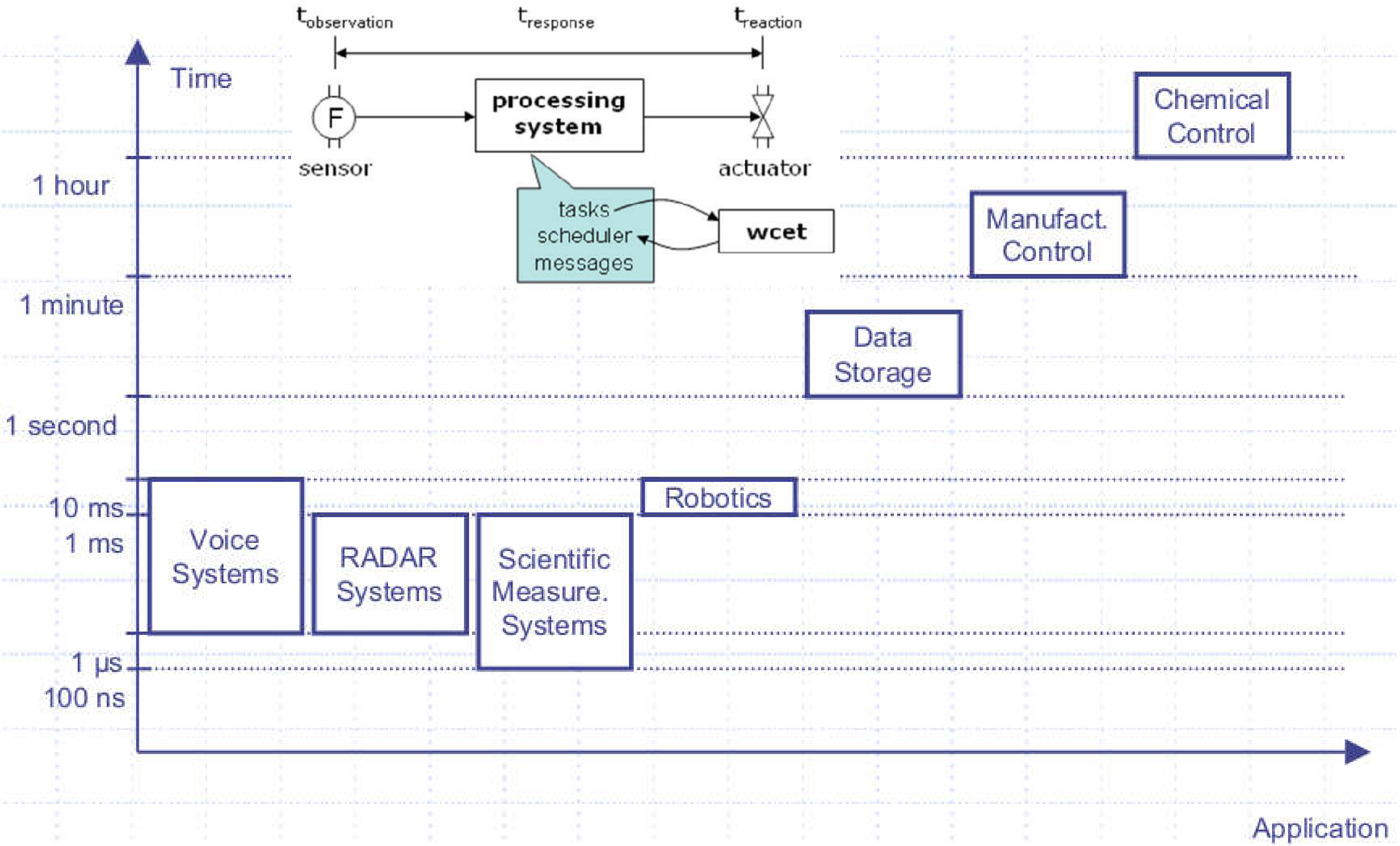
Figure 1: The real-time spectrum


Non-
real time
Soft
real time
Hard
real time
Computer
simulation
User
interface
Internet
video
Cruise
control
Tele-
communications
Flight
control
Electronic
engine

Guarantee the timing behavior of tasks


Hard Tasks
Firm Tasks
Soft Tasks
Missed Deadline
Catastrophic consequences
Result is useless, but causes no damage
Result has still some utility
Early miss detection (static)
Immediate miss detection (dynamic)
Late miss detection (dynamic)
Task
Start time
Deadline
Time

Responsiveness of RTS


$t_{observation}$
$t_{response}$
$t_{reaction}$
Time
F
processing system
sensor
actuator
tasks
scheduler
messages
wcet
1 hour
1 minute
1 second
10 ms
1 ms
1 µs
100 ns
Chemical Control
Manufact. Control
Data Storage
Robotics
Voice Systems
RADAR Systems
Scientific Measure. Systems
Application

“可用性”度量：缓急度函数

- 实时任务的松弛度(laxity)：决定优先级/实时性等
  - 实线：导弹，晚了，无效或炸错，不如不投。
  - 点线：刷卡消费，连接时间长后，不耐烦或放弃。
  - 短线：股票显示系统，允许一些数据延迟，但可用性下降很快，大的延迟造成损失

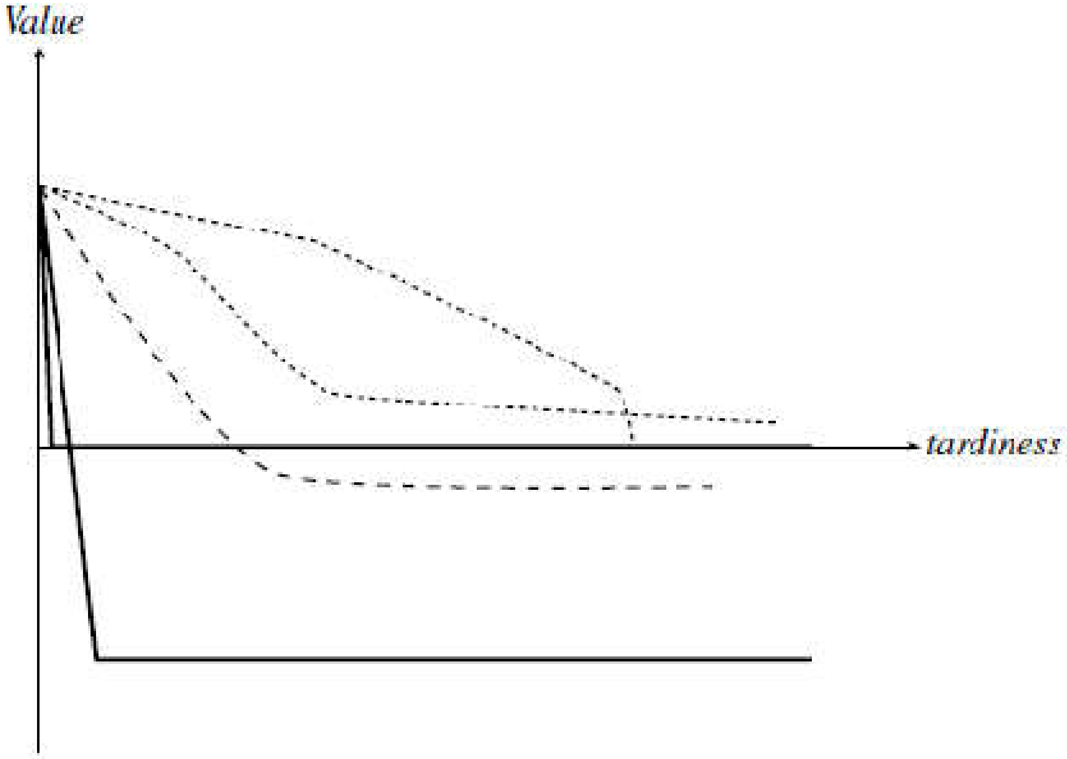


FIGURE 3–3 Examples of usefulness functions.

例：Hard RT Reactive Systems

Safety critical applications:

- Avionics, automotive, train industries, manufacturing control

Sideairbag in car, Reaction in <10 mSec

sensors:
accelerometers, wheel speed, gyroscopes, seat occupancy, brake pressure

engine controller

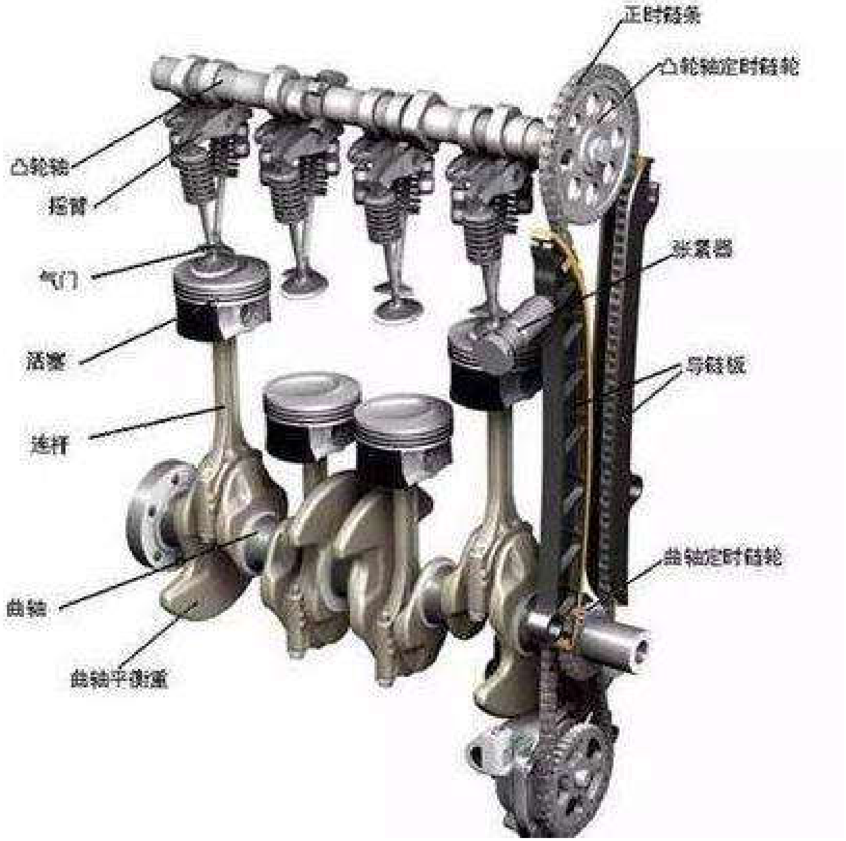
- 10 ms for 360° at 6000 rpm
- temporal accuracy of of 3 μ sec required
- up to 100 concurrent software tasks

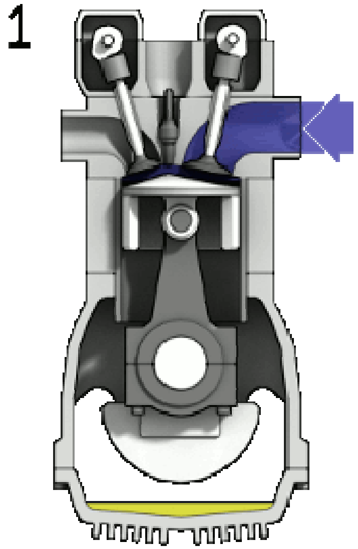
Crankcraft-synchronous tasks,

Reaction in <45 μSec

Embedded controllers must finish their tasks *within given time bounds*. Developers would like to know the *Worst-Case Execution Time (WCET)* to give a guarantee

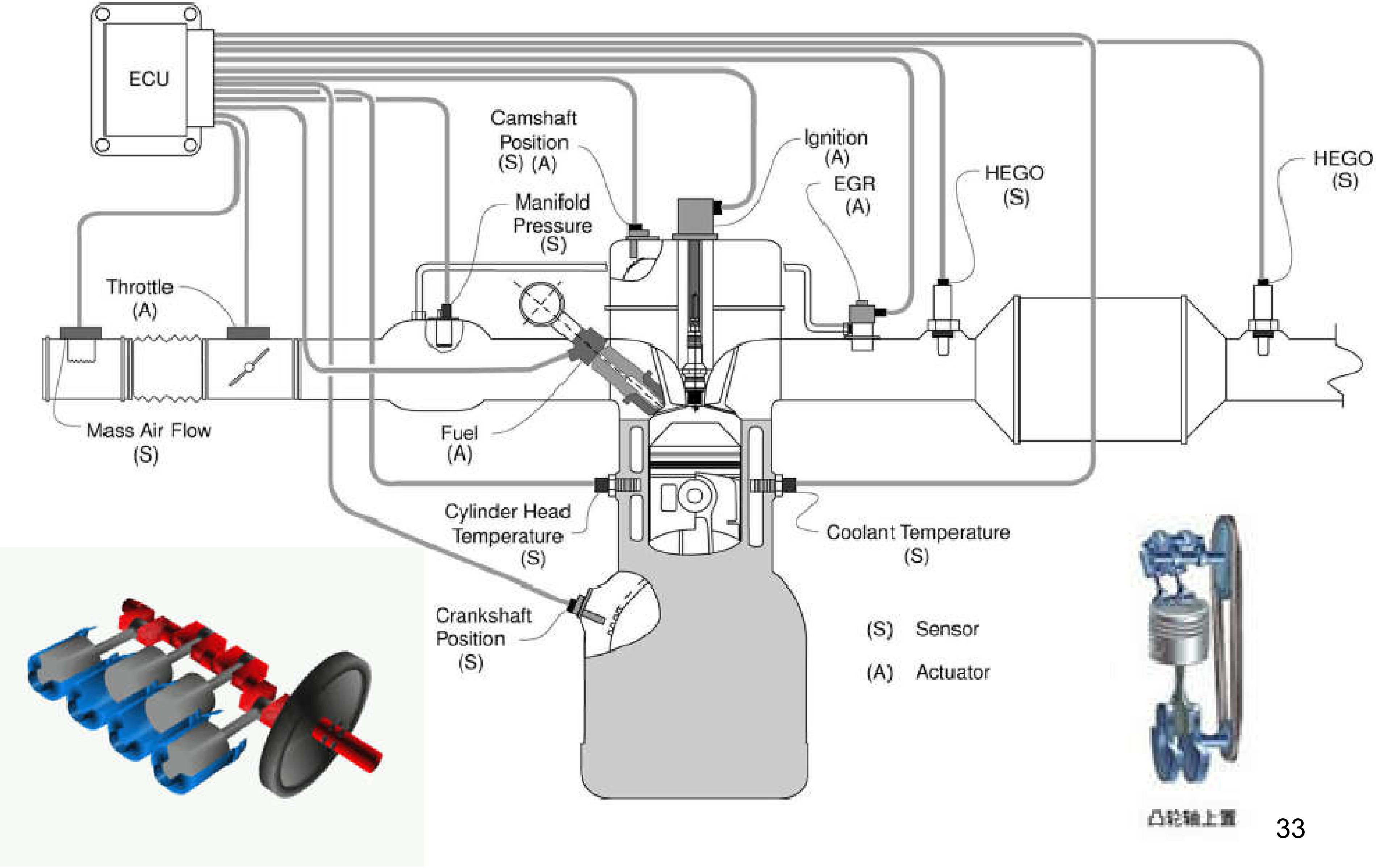
4缸引擎工作过程


正时链条
凸轮轴定时链轮
凸轮轴
摇臂
张紧器
气门
活塞
导链板
连杆
曲轴定时链轮
曲轴
曲轴平衡重



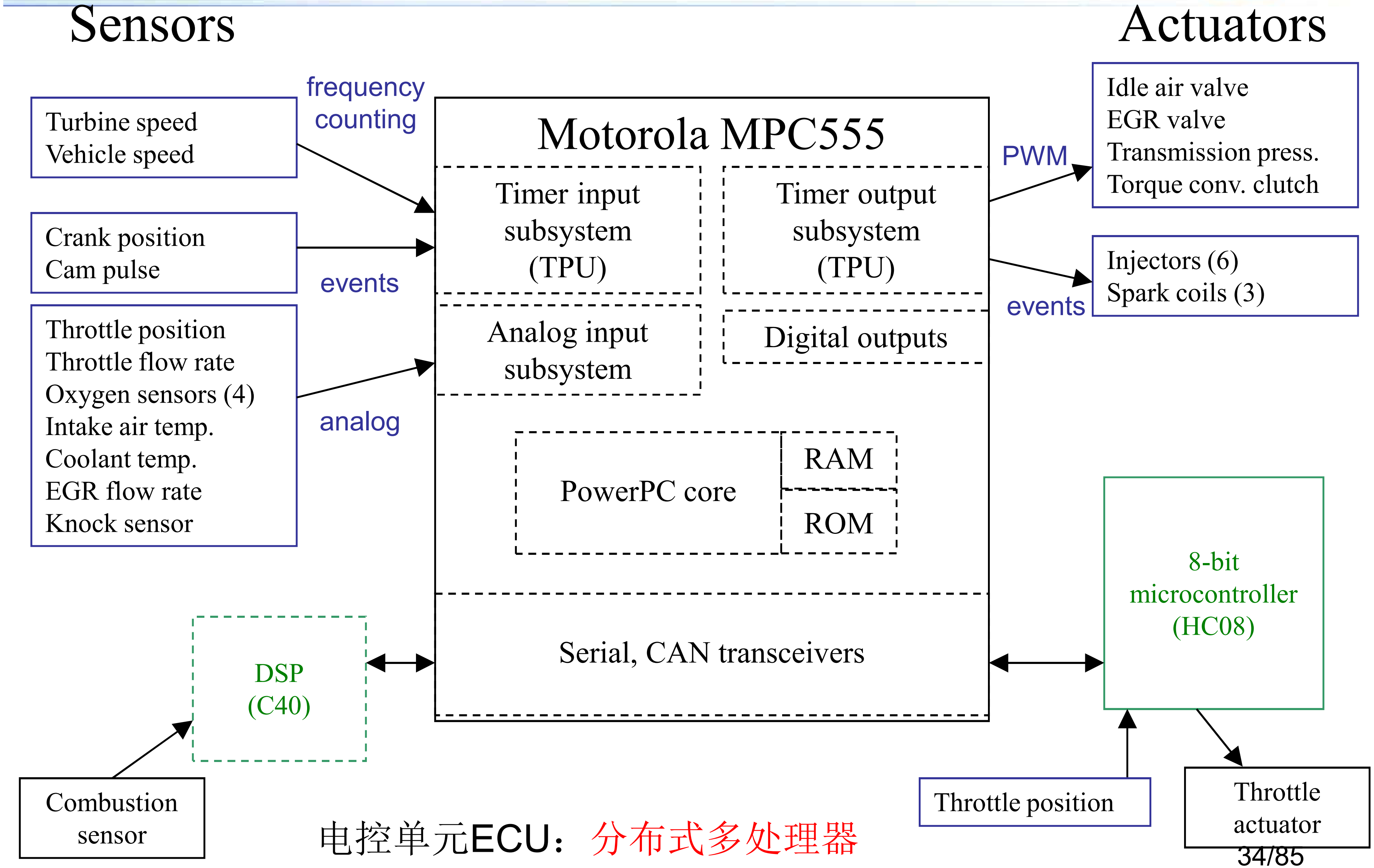
- 4冲程：吸气、压缩、做功、排气
  - 同步：曲轴转2圈，凸轮轴转1圈
    - 正时（Timing）：气门开闭

Electronic engine control system


ECU
Camshaft Position (S) (A)
Manifold Pressure (S)
Ignition (A)
EGR (A)
HEGO (S)
HEGO (S)
Throttle (A)
Mass Air Flow (S)
Fuel (A)
Cylinder Head Temperature (S)
Coolant Temperature (S)
Crankshaft Position (S)
(S) Sensor
(A) Actuator

凸轮轴上置

Powertrain Control Hardware Platform



Sensors

Actuators

Turbine speed
Vehicle speed

frequency counting

Crank position
Cam pulse

events

Throttle position
Throttle flow rate
Oxygen sensors (4)
Intake air temp.
Coolant temp.
EGR flow rate
Knock sensor

analog

Motorola MPC555

Timer input subsystem (TPU)

Timer output subsystem (TPU)

Analog input subsystem

Digital outputs

PowerPC core

RAM

ROM

Serial, CAN transceivers

PWM

Idle air valve
EGR valve
Transmission press.
Torque conv. clutch

Injectors (6)
Spark coils (3)

events

8-bit microcontroller (HC08)

DSP (C40)

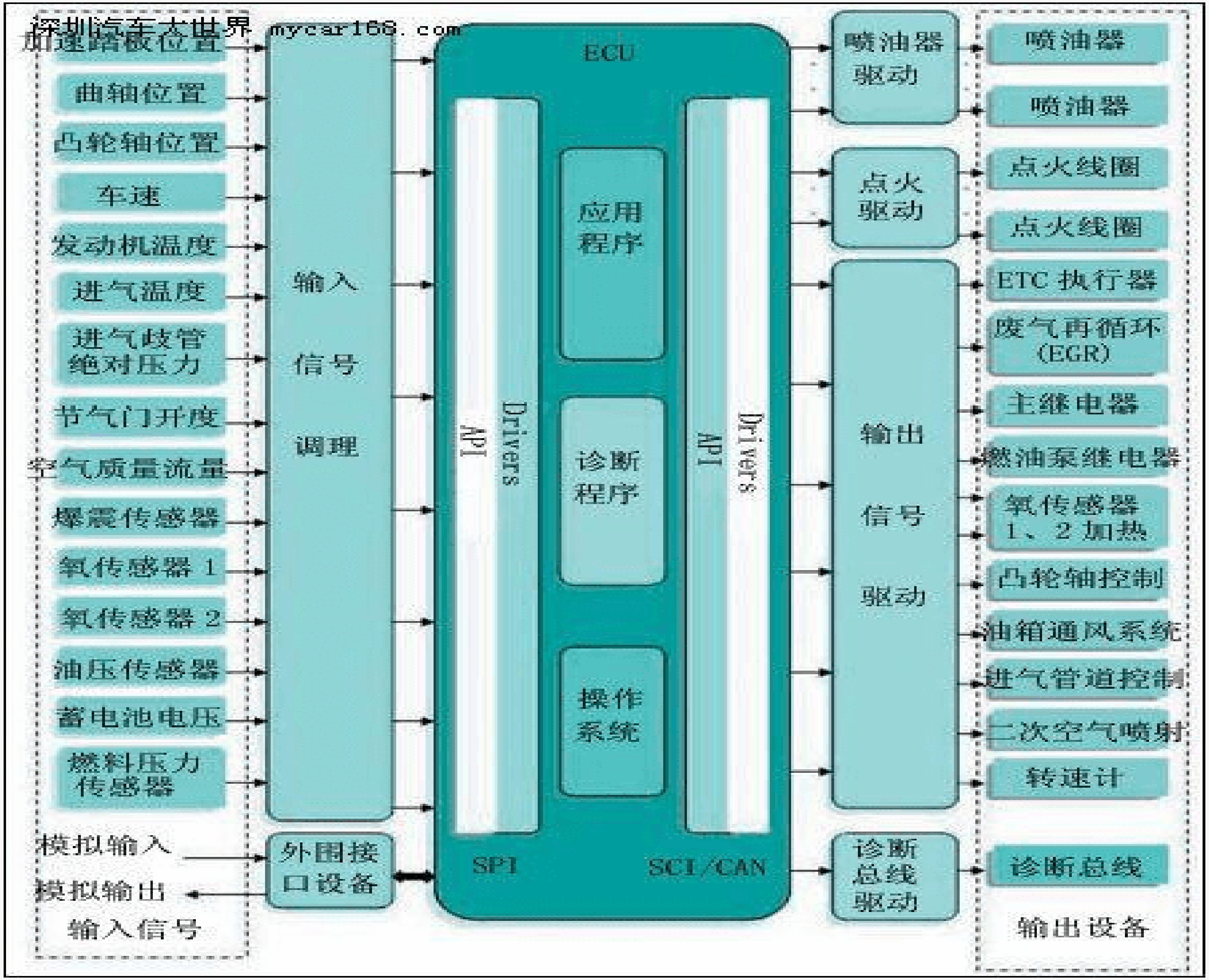
Combustion sensor

Throttle position

Throttle actuator

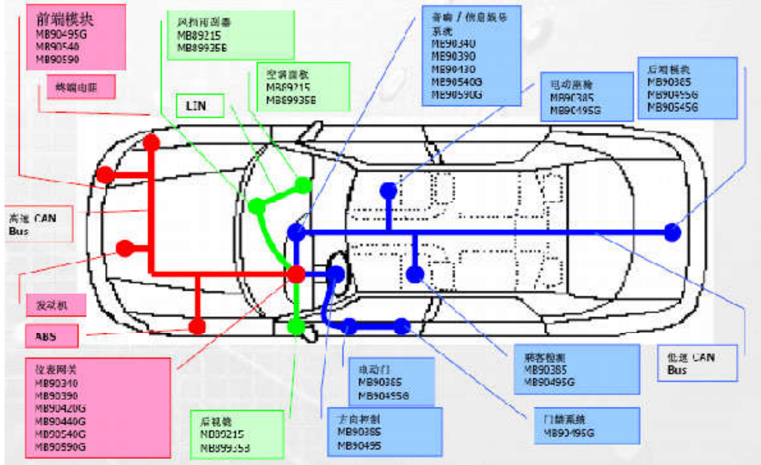
电控单元ECU：分布式多处理器

发动机管理系统EMS


深圳汽车大世界 mycar168.com
加速踏板位置
曲轴位置
凸轮轴位置
车速
发动机温度
进气温度
进气歧管绝对压力
节气门开度
空气质量流量
爆震传感器
氧传感器 1
氧传感器 2
油压传感器
蓄电池电压
燃料压力传感器
模拟输入
模拟输出
输入信号
输入信号调理
外围接口设备
ECU
API Drivers
应用程序
诊断程序
操作系统
API Drivers
SPI
SCI/CAN
喷油器驱动
点火驱动
输出信号驱动
诊断总线驱动
喷油器
喷油器
点火线圈
点火线圈
ETC 执行器
废气再循环（EGR）
主继电器
燃油泵继电器
氧传感器1、2加热
凸轮轴控制
油箱通风系统
进气管道控制
二次空气喷射
转速计
诊断总线
输出设备

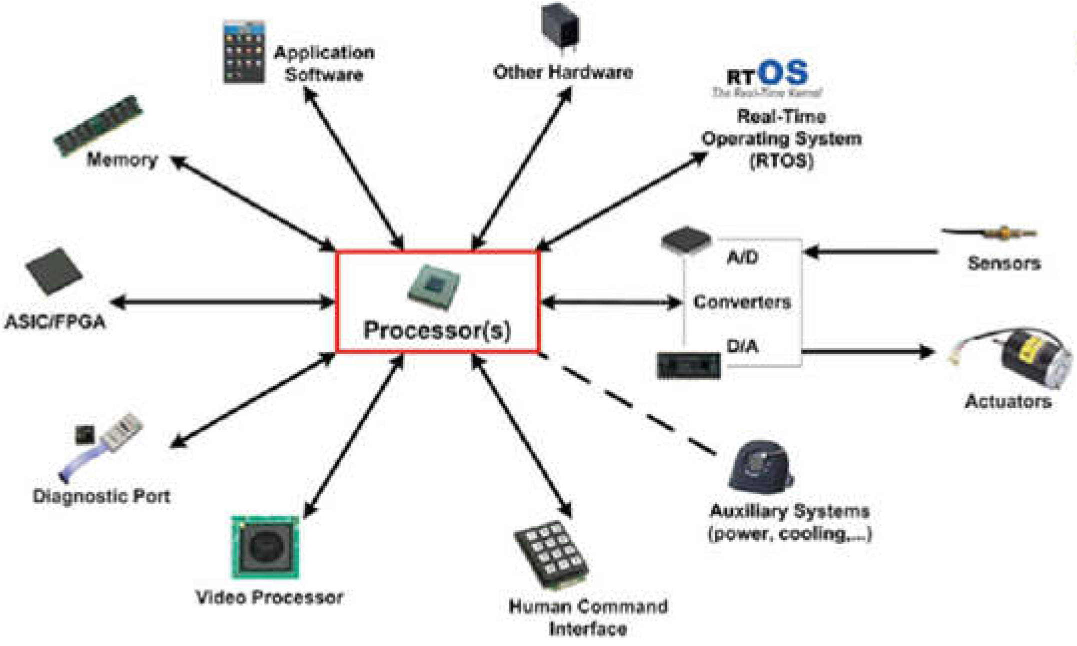
Application requirements

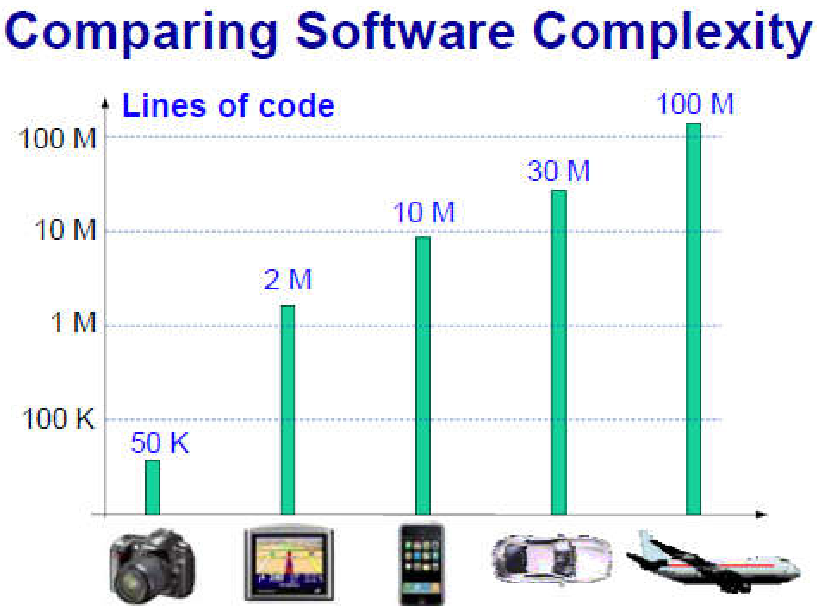
- 单芯片微控制器（15~25 MHz）
  - 如Motorola 68332, Intel i960, and Hitachi SH-2。
- 所有的ROM和RAM都位于片上
  - ROM为32~128 kB，RAM最大为4Kbytes
  - 因此RTOS代码约20 kbytes
- 单处理器或分布式（多处理器，5~10个节点）
  - 计算量（能力）要求
  - sensors与actuators分离
  - 时序约束
- 低速现场总线连接（1~2 Mbit/s）
- 10~20个并发实时任务
  - 短周期<10ms
  - 中等周期10~100ms
  - 长周期>100ms。


前端模块
MB90495G
MB90540
MB90590
终端电阻
风挡雨刷器
MB89215
MB89935B
空调面板
MB89215
MB89935B
LIN
音响 / 信息娱乐系统
MB90340
MB90390
MB90430
MB90540G
MB90590G
电动座椅
MB90385
MB90495G
后端模块
MB90385
MB90455G
MB90545G
高速 CAN Bus
发动机
ABS
仪表网关
MB90340
MB90390
MB90420G
MB90440G
MB90540G
MB90590G
后视镜
MB89215
MB89935B
电动门
MB90385
MB90455G
方向控制
MB90385
MB90495
乘客检测
MB90385
MB90495G
低速 CAN Bus
门禁系统
MB90495G

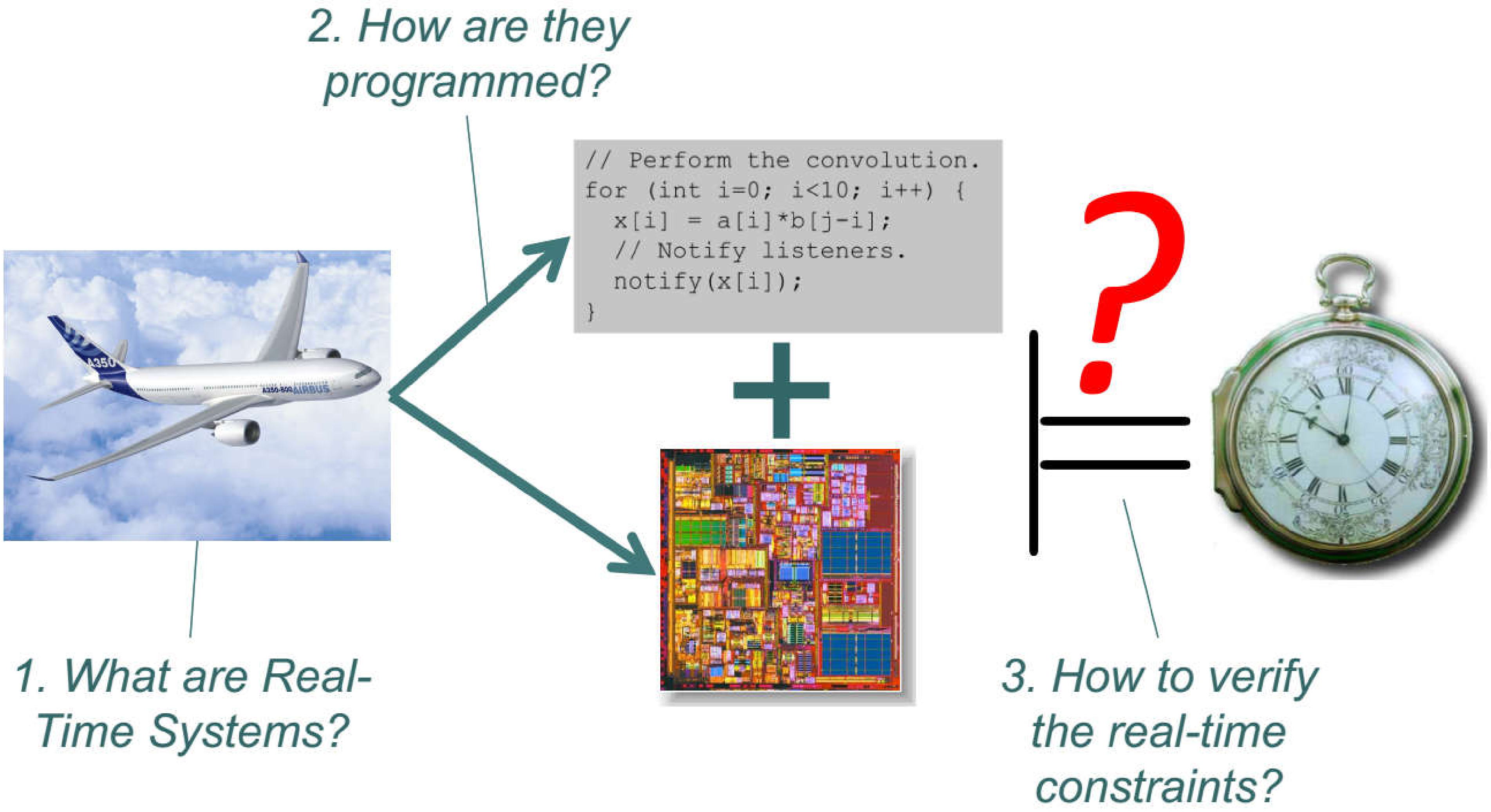
Building blocks of RT/E

- Embedded computers + Sensors + Actuators + Network
- Software now makes up 90 percent of the value of these devices.
  - More than 80% of innovations in the automotive industry are expected to result from embedded software over the next decade.


Application Software
Other Hardware
RTOS
The Real-Time Kernel
Real-Time Operating System (RTOS)
Memory
ASIC/FPGA
Processor(s)
A/D
Converters
D/A
Sensors
Actuators
Diagnostic Port
Video Processor
Human Command Interface
Auxiliary Systems (power, cooling,...)



实时软件设计



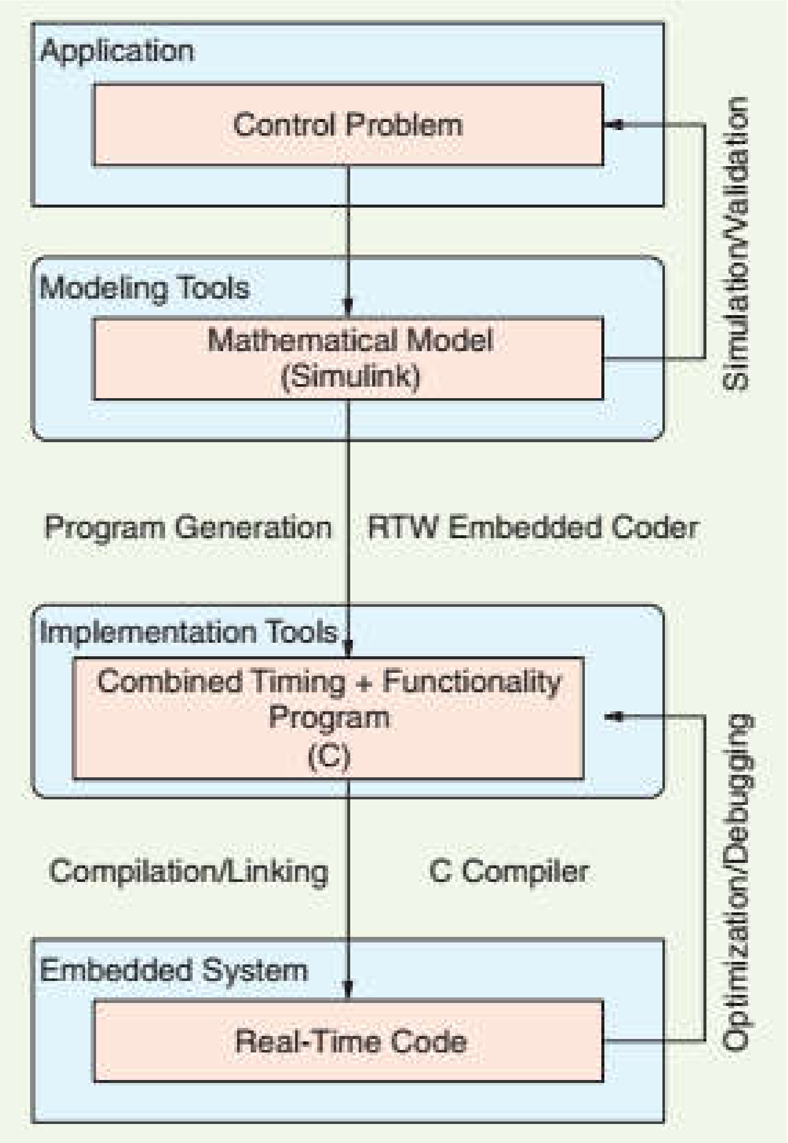
2. *How are they programmed?*

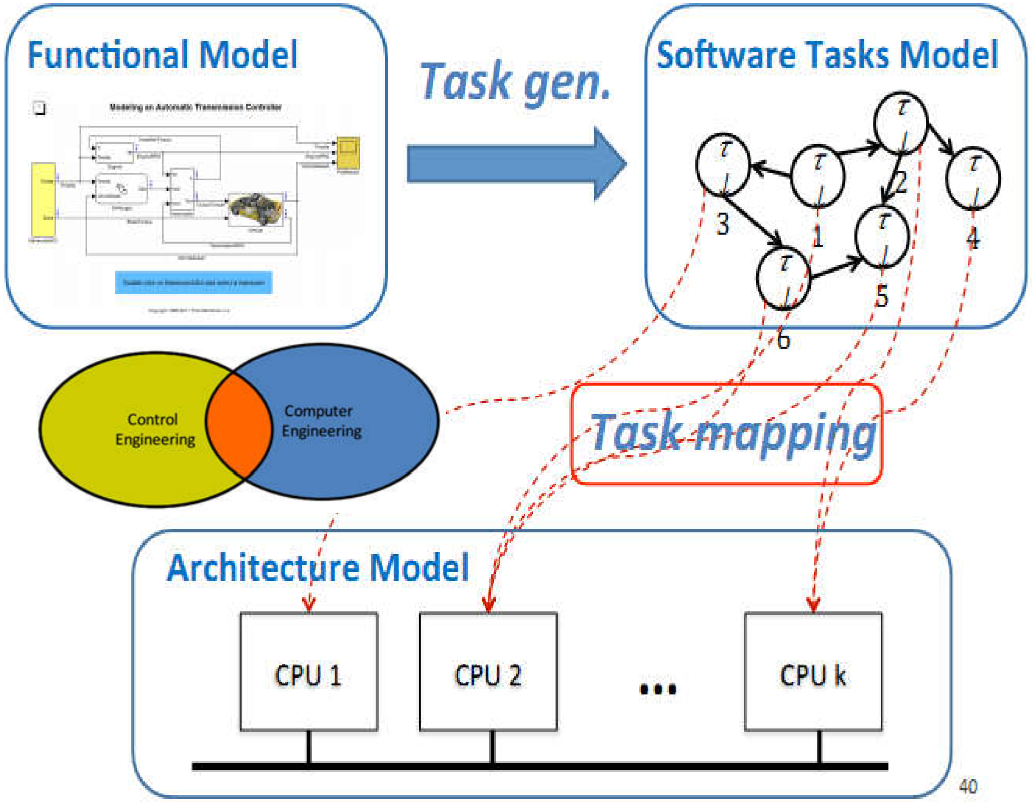
```
// Perform the convolution.
for (int i=0; i<10; i++) {
  x[i] = a[i]*b[j-i];
  // Notify listeners.
  notify(x[i]);
}
```

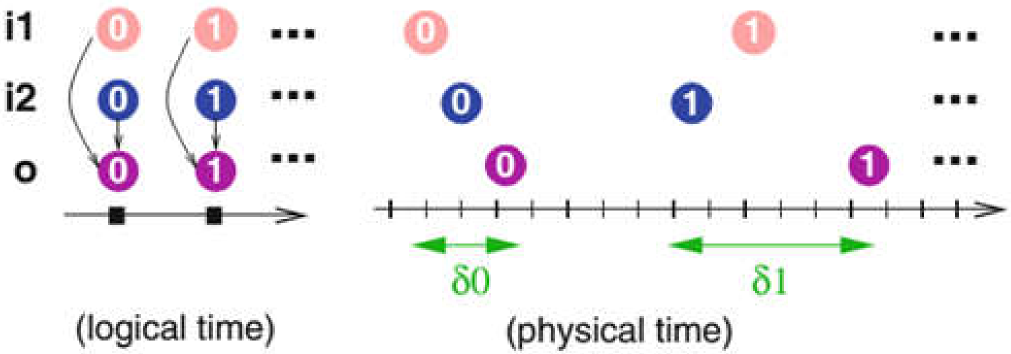
1. *What are Real-Time Systems?*

3. *How to verify the real-time constraints?*

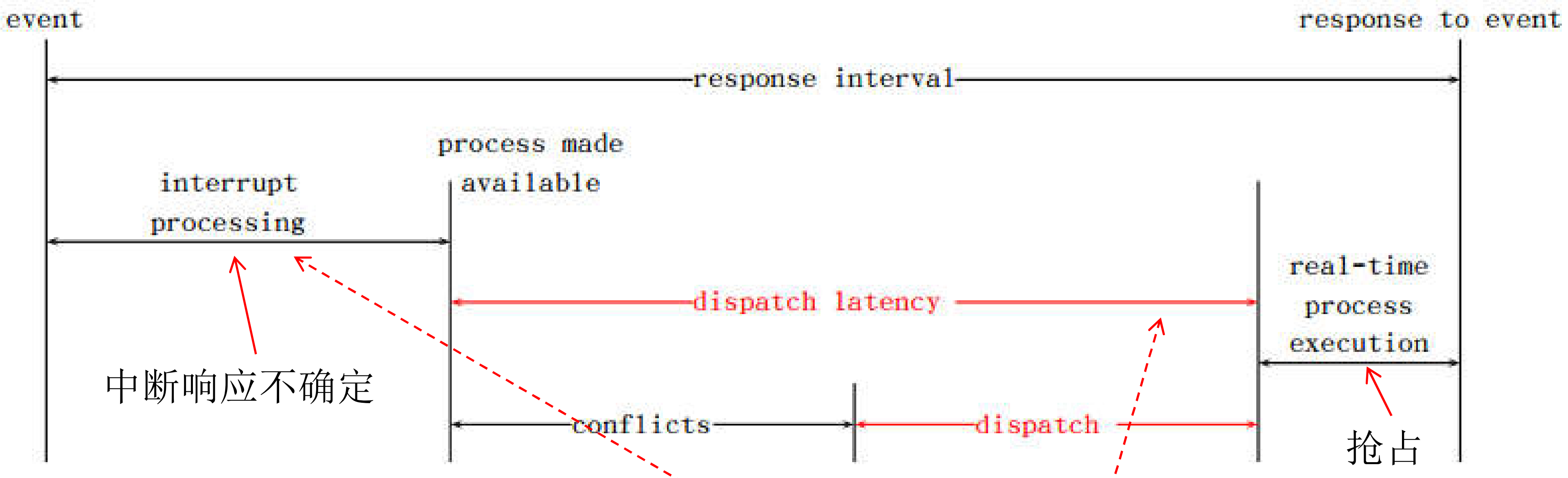
A two-steps design approach


Application
Control Problem
Modeling Tools
Mathematical Model
(Simulink)
Simulation/Validation
Program Generation
RTW Embedded Coder
Implementation Tools
Combined Timing + Functionality
Program
(C)
Compilation/Linking
C Compiler
Embedded System
Real-Time Code
Optimization/Debugging


Functional Model
Task gen.
Software Tasks Model
τ 3
τ 1
τ 2
τ 4
τ 5
τ 6
Control
Engineering
Computer
Engineering
Task mapping
Architecture Model
CPU 1
CPU 2
...
CPU k


i1
i2
o
0
1
...
δ0
δ1
(logical time)
(physical time)

CS(RTOS) view of Reaction

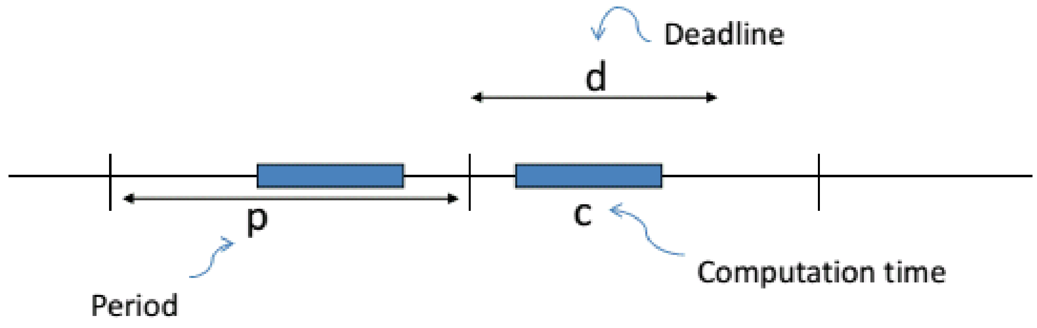

event
response to event
response interval
process made available
interrupt processing
dispatch latency
real-time process execution
conflicts
dispatch

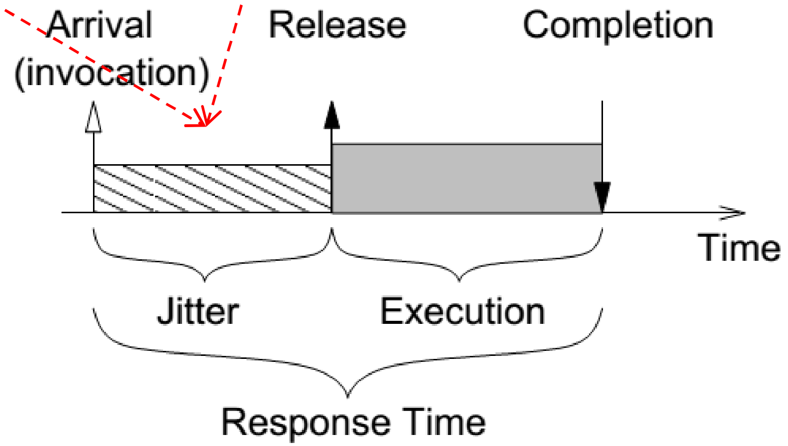
中断响应不确定

抢占

控制任务同步 vs. RTOS异步

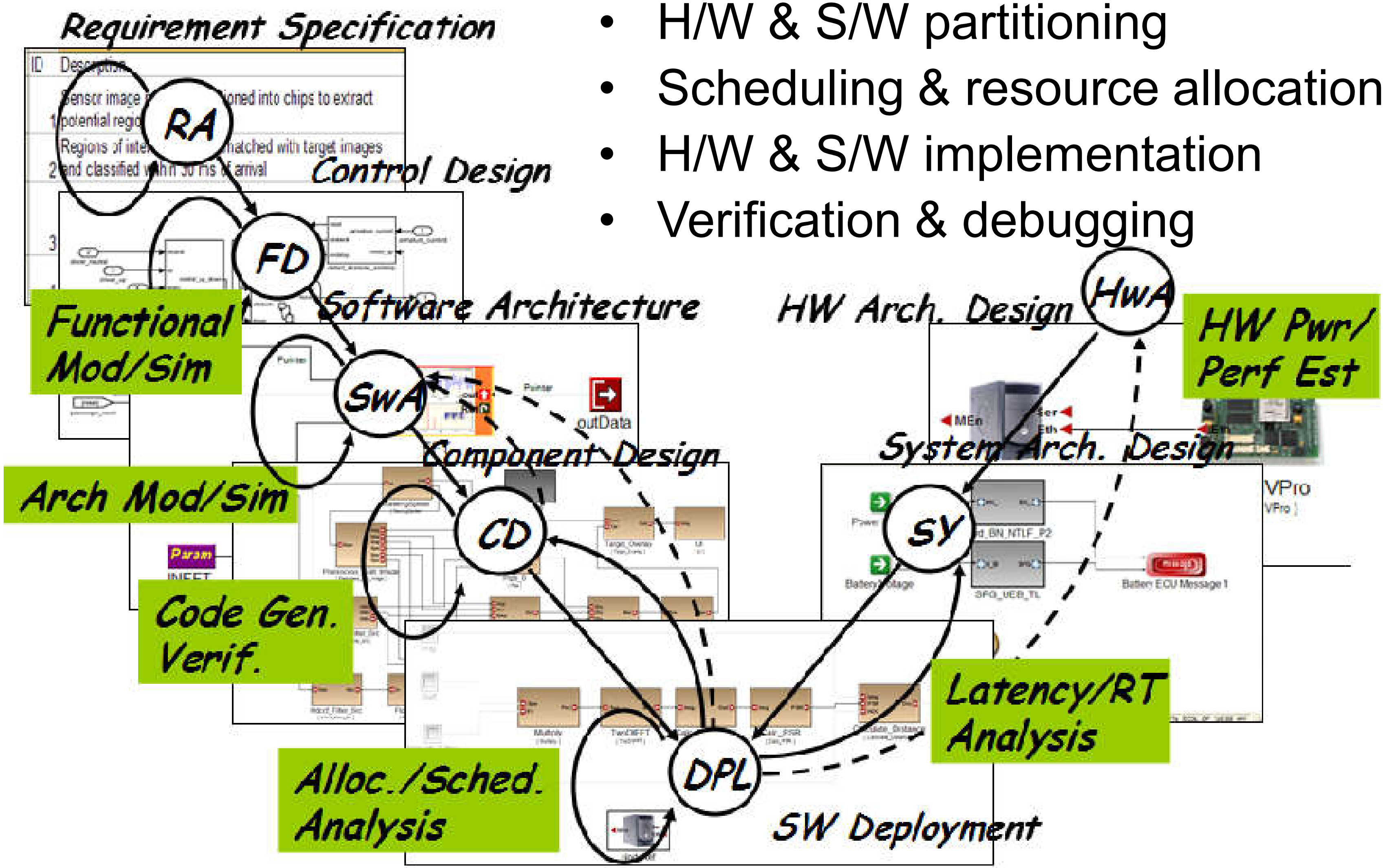
任务模型确定性vs.实现的不确定性


Deadline
d
p
c
Period
Computation time


Arrival
(invocation)
Release
Completion
Time
Jitter
Execution
Response Time

RTES系统设计过程: top-down

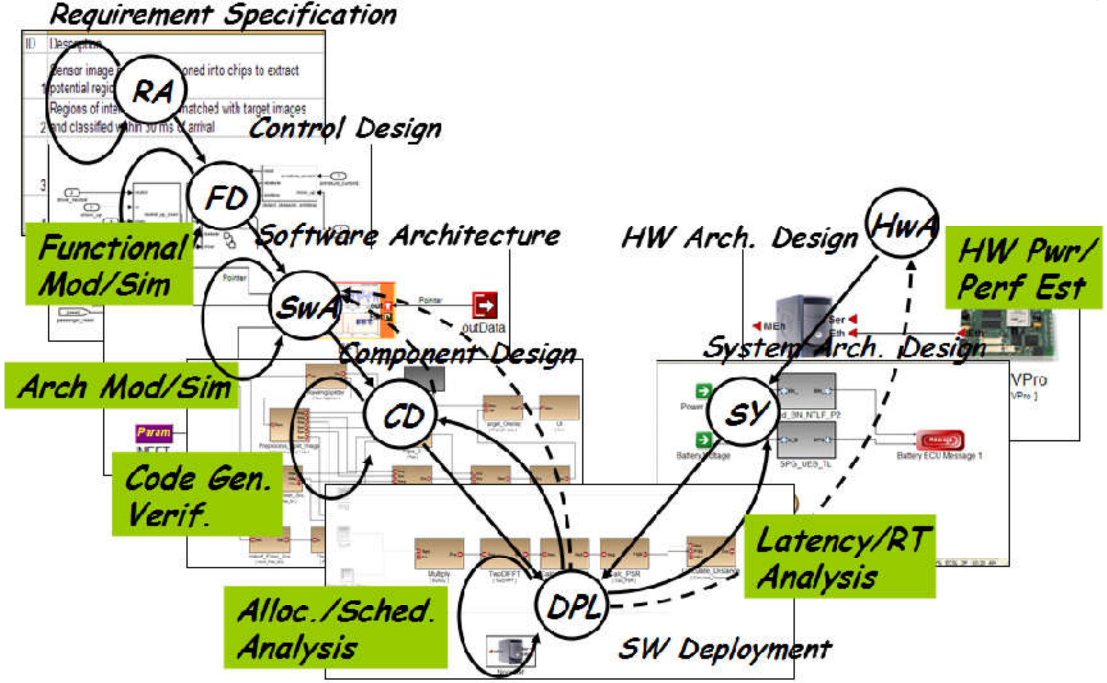
- Specification/modeling
- H/W & S/W partitioning
- Scheduling & resource allocations
- H/W & S/W implementation
- Verification & debugging

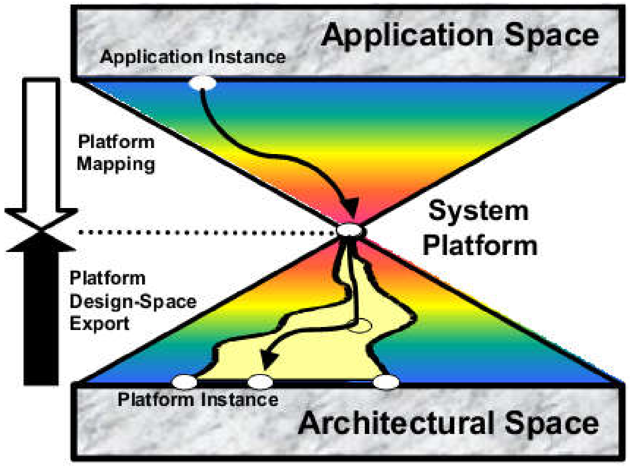

Requirement Specification
RA
Control Design
FD
Functional Mod/Sim
Software Architecture
SwA
outData
Arch Mod/Sim
Component Design
CD
Code Gen. Verif.
HW Arch. Design
HwA
HW Pwr/ Perf Est
System Arch. Design
SY
VPro
Latency/RT Analysis
DPL
Alloc./Sched. Analysis
SW Deployment

嵌入式系统设计方法与工具

- 软硬件协同设计Co-design
- Model Based Design
- Component Based Design
- Platform Based Design
  - emphasising systematic reuse

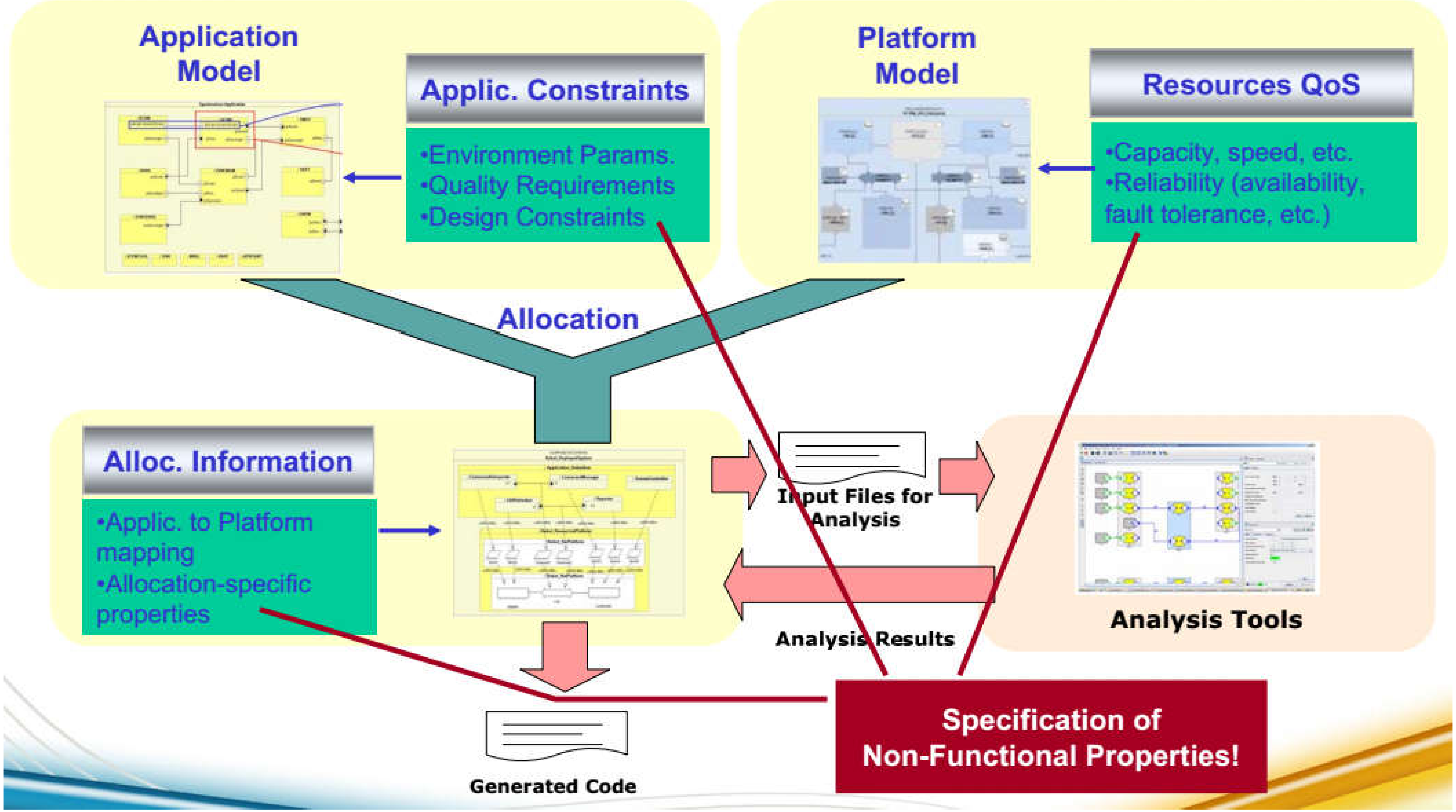
- Keil：指令级系统仿真器
- Xilinx ISE/XPS：软硬件Co-design
- SWEET：WCET分析
- GameTime：系统分析（WCET）
- Cheddar：可调度性分析
- SimSo：分布式实时系统可调度性分析
- UPPAAL：形式化验证，model checker
- Ptolemy：协同设计与仿真


Requirement Specification
RA
Control Design
FD
Functional Mod/Sim
Software Architecture
HW Arch. Design
HwA
HW Pwr/ Perf Est
SwA
Component Design
System Arch. Design
Arch Mod/Sim
CD
SY
Code Gen. Verif.
Latency/RT Analysis
DPL
Alloc./Sched. Analysis
SW Deployment


Application Space
Application Instance
Platform Mapping
System Platform
Platform Design-Space Export
Platform Instance
Architectural Space

System Platform Stack
(meeting-in-the-middle)

“Y-Chart” Approach:建模与分析



Application Model

Applic. Constraints

- Environment Params.
- Quality Requirements
- Design Constraints

Platform Model

Resources QoS

- Capacity, speed, etc.
- Reliability (availability, fault tolerance, etc.)

Allocation

Alloc. Information

- Applic. to Platform mapping
- Allocation-specific properties

Input Files for Analysis

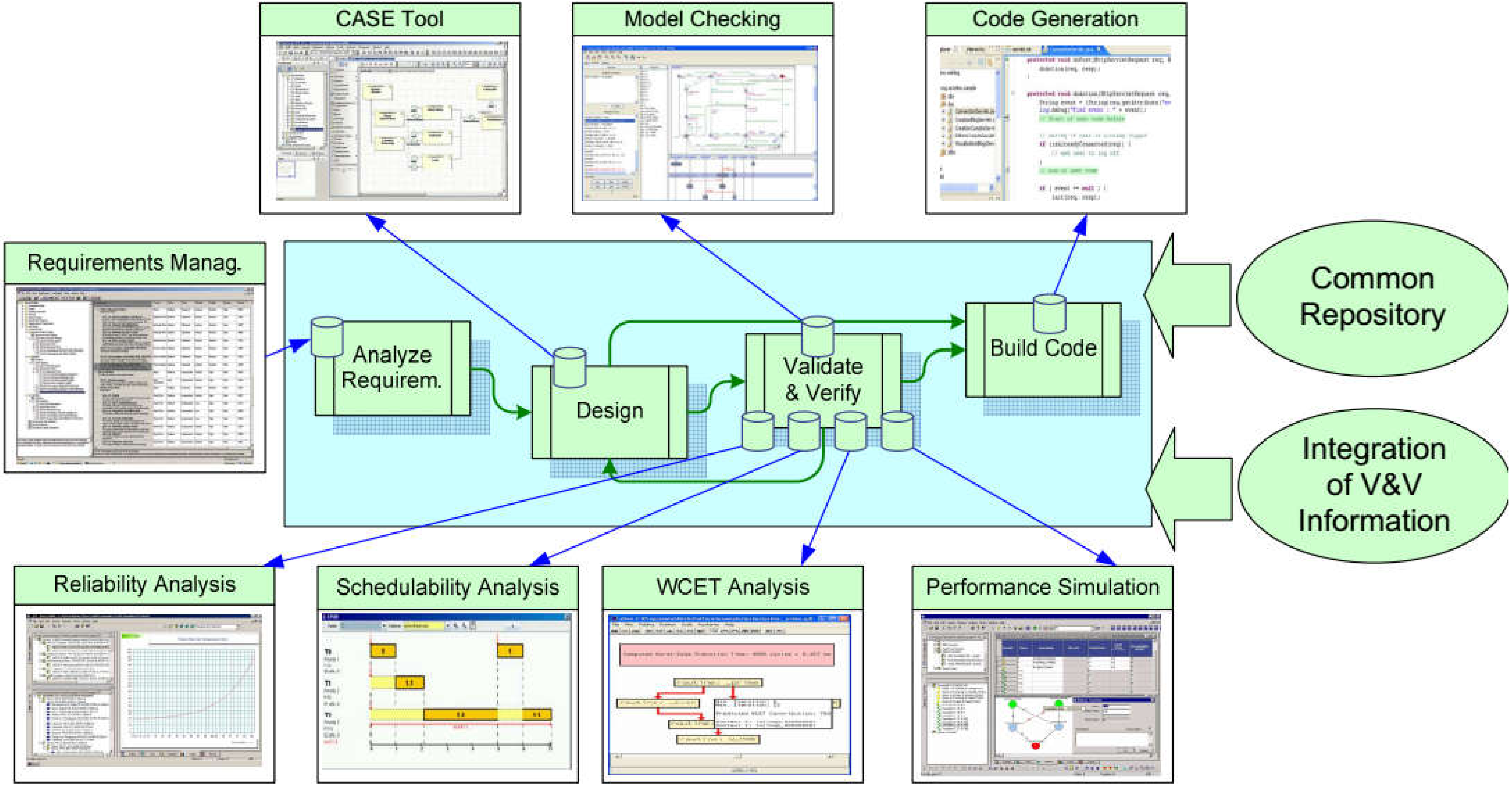
Analysis Tools

Analysis Results

Generated Code

Specification of Non-Functional Properties!

A Framework of Collaborative Environments



CASE Tool

Model Checking

Code Generation

Requirements Manag.

Analyze Requirem.

Design

Validate & Verify

Build Code

Common Repository

Integration of V&V Information

Reliability Analysis

Schedulability Analysis

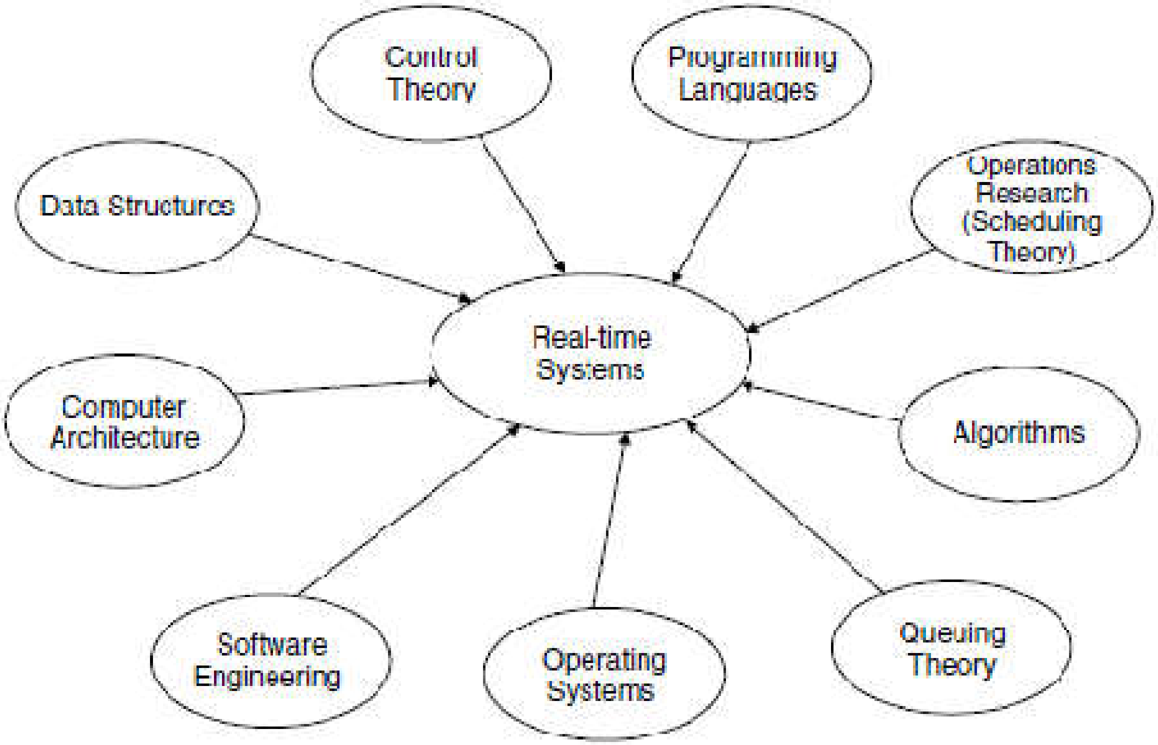
WCET Analysis

Performance Simulation

- SWEET/Chronos，SimSo/Cheddar，Truetime，Uppaal

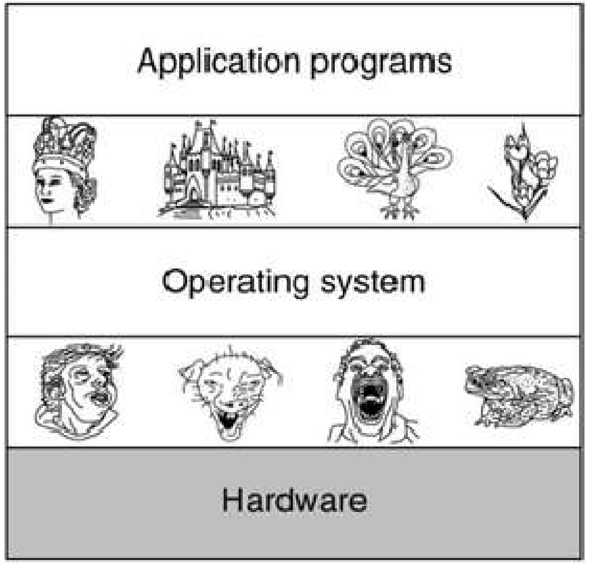
“实时嵌入式系统设计”的问题

- 系统结构
  - **处理器体系**
  - 网络体系
    - 通信协议，容错，延迟度量、预测和控制
  - 时钟同步体系
    - 同步体系，容错
  - **容错与可靠性**
- 操作系统
  - **任务分配与调度**
  - 通信协议
  - 差错管理与恢复
  - 时钟同步算法
- 编程语言
- 分布式架构
- 评估、验证

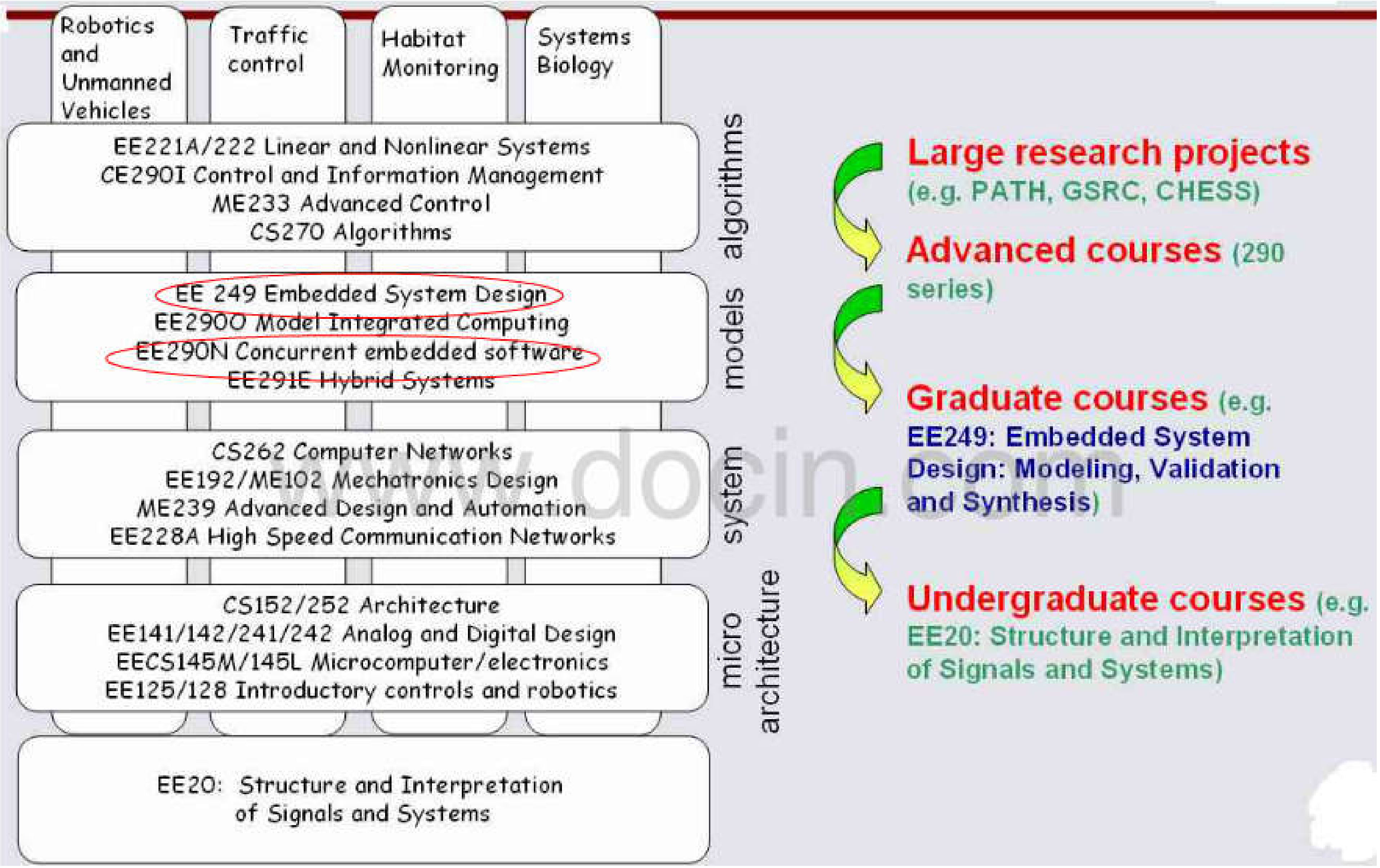

Control Theory
Programming Languages
Data Structures
Operations Research (Scheduling Theory)
Real-time Systems
Computer Architecture
Algorithms
Software Engineering
Operating Systems
Queuing Theory

知识范畴

- Computing "stack"
  - Applications
  - Programming language
  - Compiler
  - Runtime
  - *Virtual machine*
  - Operating system
  - *Hypervisor*
  - Architecture
  - Microarchitecture


Application programs
Operating system
Hardware

UCB嵌入式系统研究与教学体系



Robotics and Unmanned Vehicles
Traffic control
Habitat Monitoring
Systems Biology

EE221A/222 Linear and Nonlinear Systems
CE290I Control and Information Management
ME233 Advanced Control
CS270 Algorithms

EE 249 Embedded System Design
EE290O Model Integrated Computing
EE290N Concurrent embedded software
EE291E Hybrid Systems

CS262 Computer Networks
EE192/ME102 Mechatronics Design
ME239 Advanced Design and Automation
EE228A High Speed Communication Networks

CS152/252 Architecture
EE141/142/241/242 Analog and Digital Design
EECS145M/145L Microcomputer/electronics
EE125/128 Introductory controls and robotics

EE20: Structure and Interpretation
of Signals and Systems

algorithms
models
system
micro architecture

Large research projects
(e.g. PATH, GSRC, CHESS)

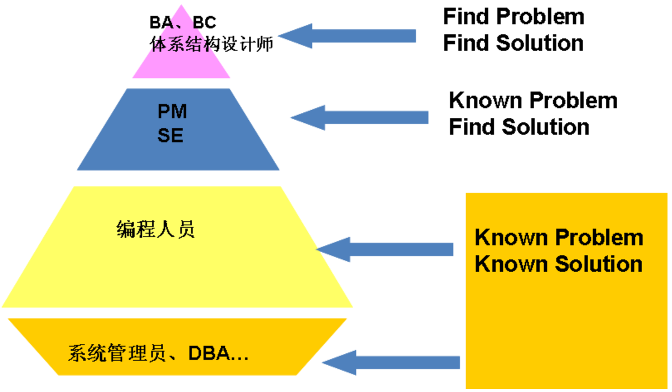
Advanced courses (290 series)

Graduate courses (e.g.
EE249: Embedded System Design: Modeling, Validation and Synthesis)

Undergraduate courses (e.g.
EE20: Structure and Interpretation of Signals and Systems)

www.docin.com

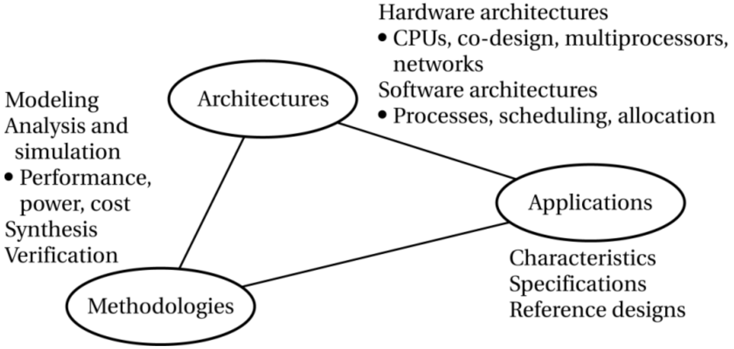
本课程目标


BA、BC
体系结构设计师
PM
SE
编程人员
系统管理员、DBA…
Find Problem
Find Solution
Known Problem
Find Solution
Known Problem
Known Solution

- Prerequisites
  - Computer Organization
  - *Computer Architecture*
  - Operating Systems
  - *Distributed Computer System*
- 针对“实时嵌入式系统”的设计方法
  - 重点设计与分析方法，而不是简单的软硬件实现！
  - Understanding of the broad concept of RTES
    - Learn major issues in Real-time Computing
    - Practical understanding for industry
  - To stimulate research interest

《实时嵌入式系统设计方法》要点

- 系统级和模型驱动的工程化设计方法
  - 设计、实现、验证
- 讨论RTE系统实现过程中的关键问题
  - 软硬件协同设计、CBD、MBD方法
  - 系统运行环境
    - 硬件环境：Cortex-M处理器，I/O控制
    - RTOS：uc/OS
    - SOPC方法
  - 实时软件设计方法
    - 控制系统软件设计
    - DARTS方法
    - 任务同步与通信
  - 实时任务调度：单处理器，多处理器
  - 设计描述与验证方法
  - 分布式实时系统：实时网络通信，时钟同步
  - 低功耗设计、性能分析、可靠性（Fault-Tolerant）



Architectures

Hardware architectures
- CPUs, co-design, multiprocessors, networks

Software architectures
- Processes, scheduling, allocation

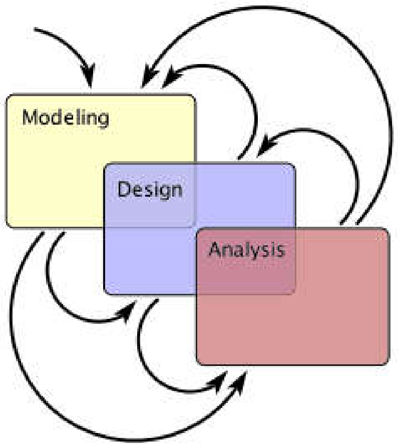
Applications

Characteristics
Specifications
Reference designs

Methodologies

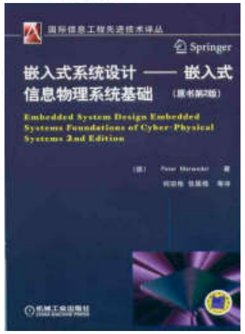
Modeling
Analysis and simulation
- Performance, power, cost

Synthesis
Verification



参考资料

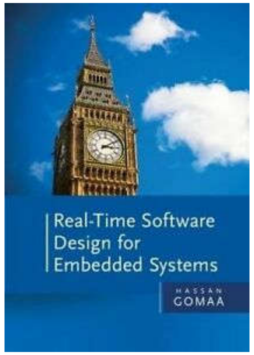
- 涉及多领域多学科，没有一本完整适用的教材！
  - 《嵌入式实时系统设计方法大纲》？
- Peter Marwedel，TU Dortmund教授
  - Embedded System Design: Embedded Systems Foundations of Cyber-Physical Systems，2nd Edition，2011/译
    - 《嵌入式系统设计·嵌入式CPS系统基础》，2013
    - 总体介绍嵌入式系统的设计模式与方法，从系统规范与建模、嵌入式硬件、嵌入式操作系统、系统的评估与验证、应用程序的实现与优化等方面，对信息物理系统的嵌入式设计进行了讲述。**——无DRT**


嵌入式系统设计 —— 嵌入式信息物理系统基础
Embedded System Design Embedded Systems Foundations of Cyber-Physical Systems 2nd Edition
Springer

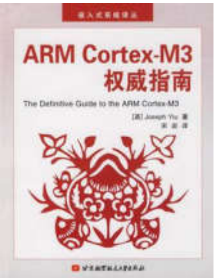
- Hermann Kopetz，TU Vienna教授
  - Real-Time Systems: Design Principles for Distributed Embedded Applications，2nd Edition，2011/译，被引2700+

Real-Time Systems Series
Hermann Kopetz
Real-Time Systems
Design Principles for Distributed Embedded Applications
Second Edition
Springer

- Hassan Gomaa，George Mason大学教授
  - Real-Time Software Design for Embedded Systems，2016/2018译
    - 采用SysML、UML和MARTE从用例到完整软件体系结构，应用COMET/RTE设计方法。


Real-Time Software Design for Embedded Systems
HASSAN GOMAA

- Joseph Yiu，姚文详，英国
  - 《ARM Cortex-M3权威指南》，第三版，2015
- Jean J. Labrosse
  - 《嵌入式实时操作系统μC/OS-II》，第二版，2002


ARM Cortex-M3 权威指南
The Definitive Guide to the ARM Cortex-M3

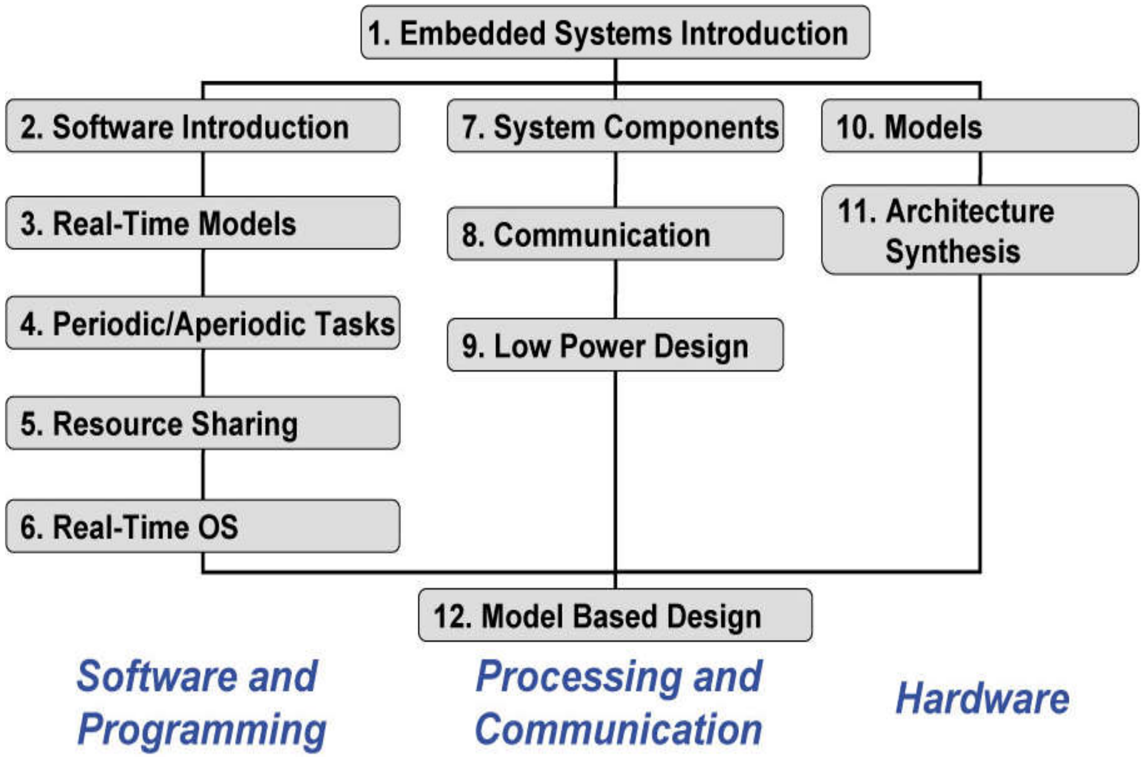
嵌入式实时操作系统
μC/OS-II（第2版）
MicroC/OS-II The Real-Time Kernel Second Edition
CHINA-PUB.COM
CMPBooks

RTES/DRT参考课件

- Peter Marwedel，Technische Universität Dortmund
  - 《嵌入式系统设计·嵌入式CPS系统基础》
- RTS课TUDresden2018
  - 教材-Kopetz和Liu
- Giorgio C. Buttazzo，TeCIP Institute，Italy
  - Hard_Real-Time_Computing_Systems
- Lothar Thiele，ETH Zurich
  - 使用Peter和Buttazzo
- Peter Puschner，TU Wien，Vienna
  - rts-wcet两门课
- Mantis Cheng，University of Victoria
  - Design and Analysis of Real Time
- Philip Koopman，CMU
  - Distributed Embedded Systems

知识点：理论+系统

- 实时嵌入式系统设计方法：设计、实现、验证
  - 设计：event-action，软硬件协同设计，MBD，CBD，MARTE
  - 实现：硬件平台，操作系统，任务调度，编程模型，DRT
  - 验证：可调度性（RMA、RTA），系统性质（建模与仿真，model checking）



1. Embedded Systems Introduction

2. Software Introduction

3. Real-Time Models

4. Periodic/Aperiodic Tasks

5. Resource Sharing

6. Real-Time OS

7. System Components

8. Communication

9. Low Power Design

10. Models

11. Architecture Synthesis

12. Model Based Design

Software and Programming

Processing and Communication

Hardware

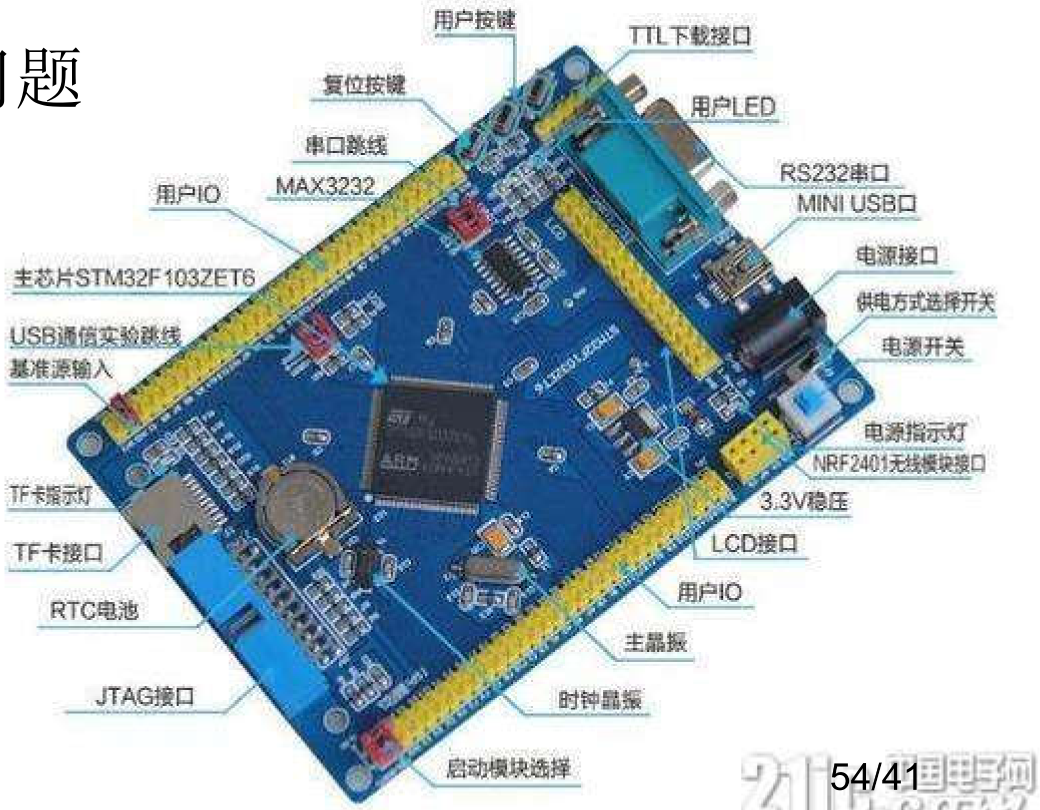
课程要求

- 课程考核方式
  - 上课30%，作业30%
  - 实验：35%
    - 2人一组
    - 四个实验报告：实验一，实验二，实验三/四/五，实验六/七
  - 期末：5%（可能调整？）

- 实验一：STM32程序设计，Keil工具
  - 冒泡排序（个人ID）
- 实验二：最小系统设计，Keil工具
  - ucOSII移植与软件系统性能分析
- 实验三：WCET分析（EMSBench），SWEET/GameTime
- 实验四：可调度性仿真分析（EMSBench），SimSo/Cheddar
- 实验五：建模与验证：交通灯，UPPAAL(Model Checking)
- 实验六：基于TDMA的分布式实时系统分析，TrueTime(用其示例)
- 实验七：实时嵌入式系统级**异构建模**与仿真，Ptolemy

实验报告内容

- 20分钟的ppt
  - 实验目标
  - 基本原理与过程
  - 问题与解决
  - 总结：收获、遗留问题
  - 实验参考文献


用户按键
TTL下载接口
复位按键
用户LED
串口跳线
RS232串口
用户IO
MAX3232
MINI USB口
电源接口
主芯片STM32F103ZET6
供电方式选择开关
USB通信实验跳线
基准源输入
电源开关
电源指示灯
NRF2401无线模块接口
TF卡指示灯
3.3V稳压
TF卡接口
LCD接口
RTC电池
用户IO
主晶振
JTAG接口
时钟晶振
启动模块选择
21ic.com 中国电子网

嵌入式系统的发展历史

- 60～70’s
  - 制造业
    - 1962年，美国一个乙烯厂实现工业装置中的直接数字化控制（DDC）
    - 1963年，DEC公司PDP11系列单扳机
  - 航天领域
    - 1965年，Gemini3号采用机载数字计算机控制
    - 1968年，阿波罗4号、土星5号
- 70～90’s
  - 1973年，微处理器出现，8085、Z80单扳机
  - 80年代初，单片机出现，8051
  - 1982年，DSP出现，高速数字信号实时处理
    - 比同期的通用CPU快10～50倍
  - 80年代初，RTOS出现（pSOS、VxWorks、QNX）

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嵌入式系统的发展历史（con’t）

- 90’s
  - 应用普及
    - Of 4 billions microprocessors/microcontrollers sold per year, 95% are for embedded products
    - 汽车：50个嵌入式微处理器
      - “福特公司所出售的计算能力已超过IBM”
    - 飞机：十几个嵌入式系统，上百个单片机
  - 32位微处理器
  - 嵌入式操作系统所占比例越来越高
    - 早期：10％
    - 90’s初期：30％
    - 90’s后期：80％～90％
  - 开发工具越来越丰富

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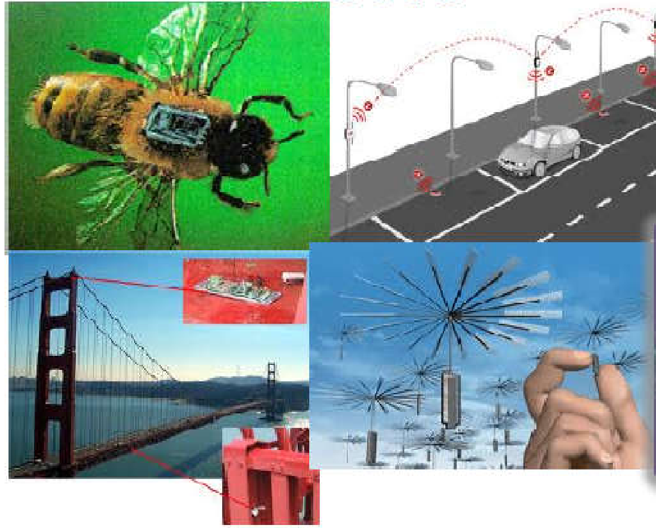
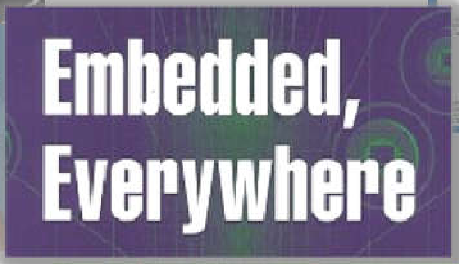
嵌入式实时系统研究

- 70’s：基础
  - 编程语言：PEARL/1978，ESTEREL/1983，Modula-2/1982
  - 调度算法：程序员自己调度
- 85’s：普及
  - RTOS：VxWorks 1983，uc/OS 1992
  - 分布式实时系统，多处理器系统
- 90’s：标准化
  - Ada 92~95，OSEK/VDX 93
- 00’s：设计方法
  - MBD、CBD、PBD
  - AADL 01~04，Autosar 03，TTA 03，Giotto 03
- 05’s：万物互联
  - Multicore，MARTE 07，IoT 04，CPS 06
- 10’s：MCS
- 15’s：ACPS，边缘计算

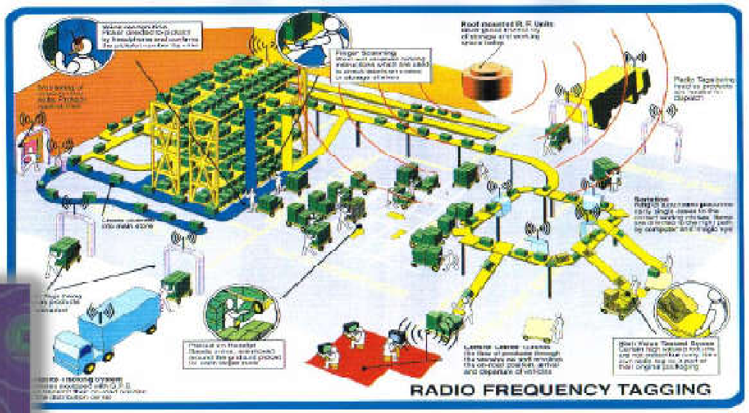
Embedded Systems：*embedded computing*

Sensors



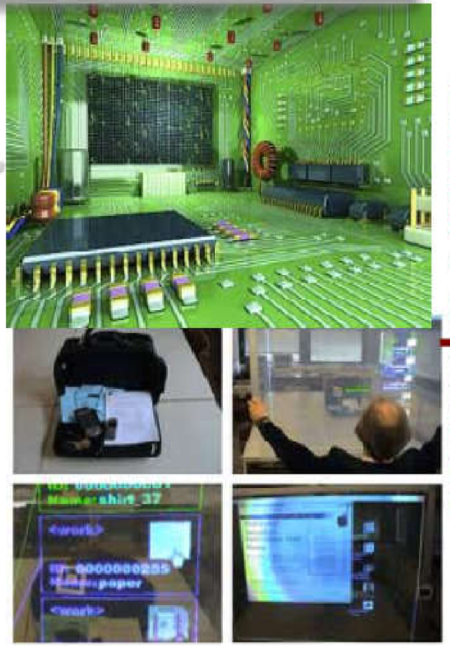

Embedded,
Everywhere

Industrial

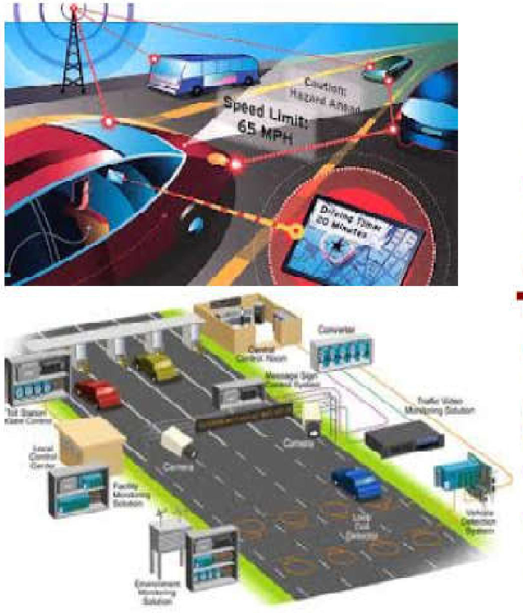

RADIO FREQUENCY TAGGING

Medical

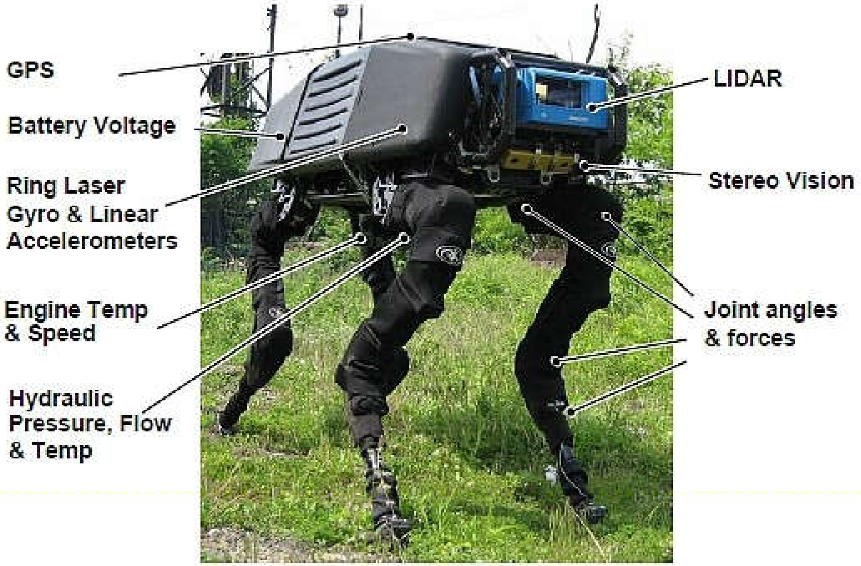
Smart Spaces



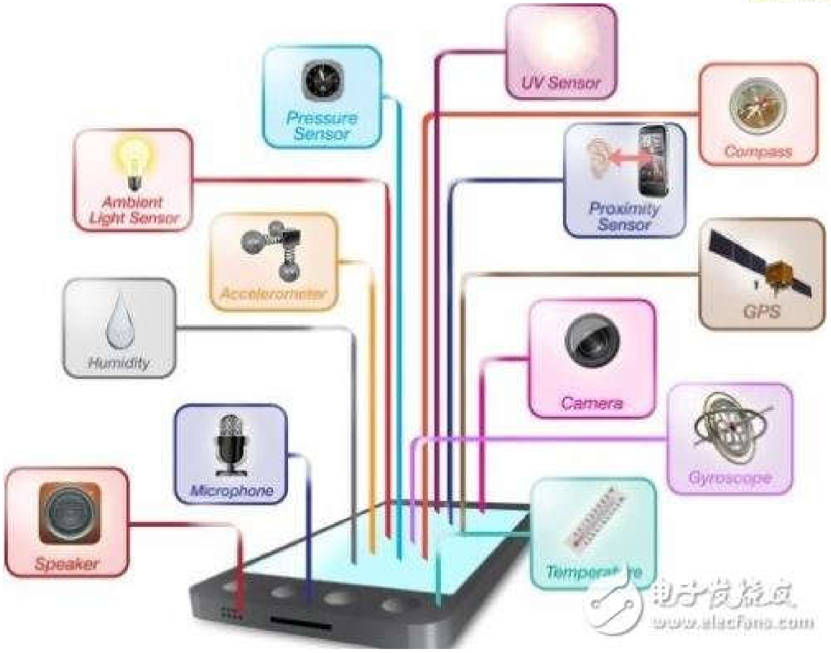
Transportation


Caution: Hazard Ahead
Speed Limit: 65 MPH
Driving Time 20 Minutes

智能传感器

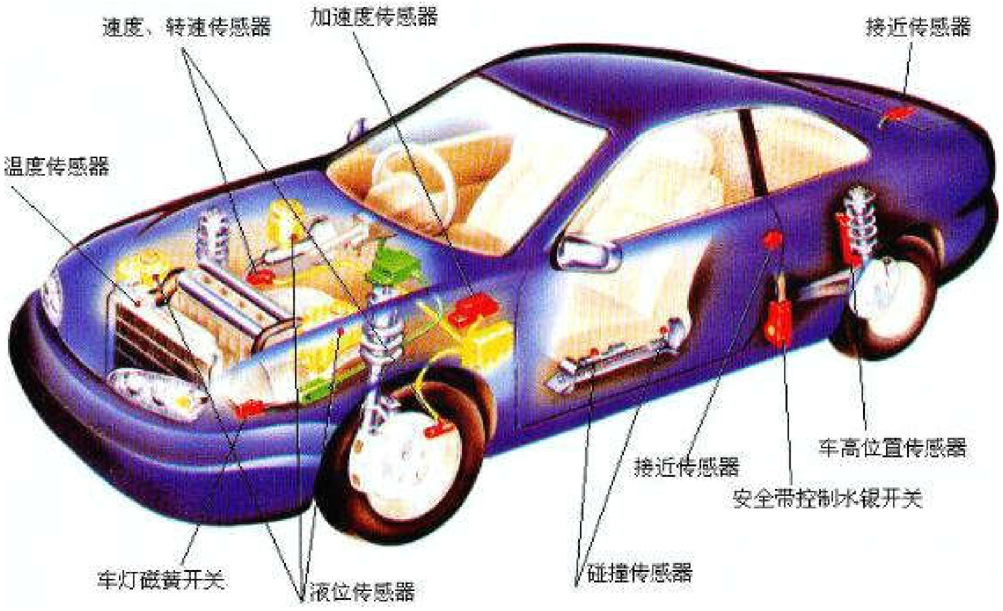


GPS
Battery Voltage
Ring Laser Gyro & Linear Accelerometers
Engine Temp & Speed
Hydraulic Pressure, Flow & Temp
LIDAR
Stereo Vision
Joint angles & forces



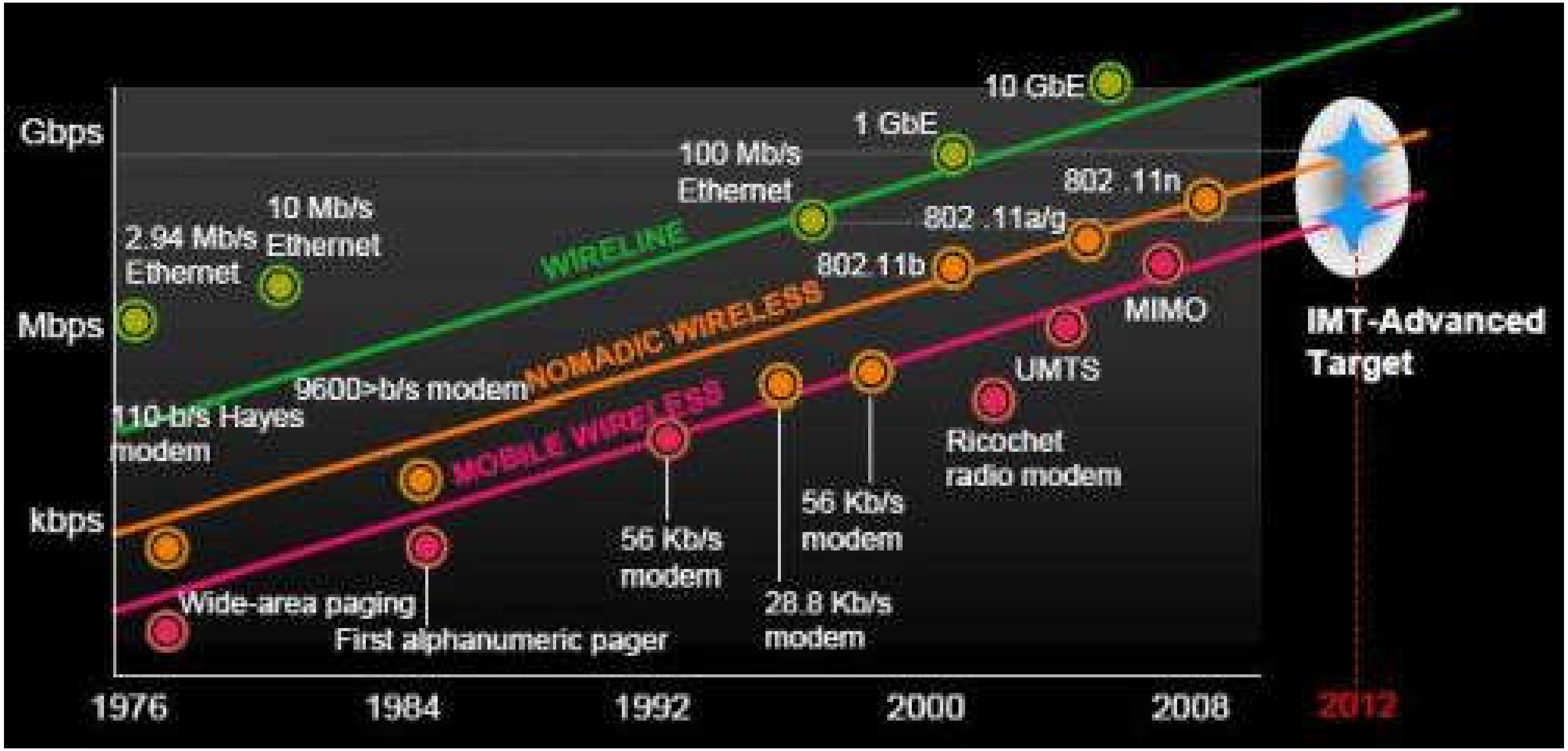
UV Sensor
Pressure Sensor
Compass
Ambient Light Sensor
Proximity Sensor
Accelerometer
GPS
Humidity
Camera
Microphone
Gyroscope
Speaker
Temperature

电子发烧友 www.elecfans.com



速度、转速传感器
加速度传感器
接近传感器
温度传感器
车高位置传感器
接近传感器
安全带控制水银开关
车灯磁簧开关
液位传感器
碰撞传感器

Edholm通信定律



- 5G：带宽10G，延迟1ms。感知网络

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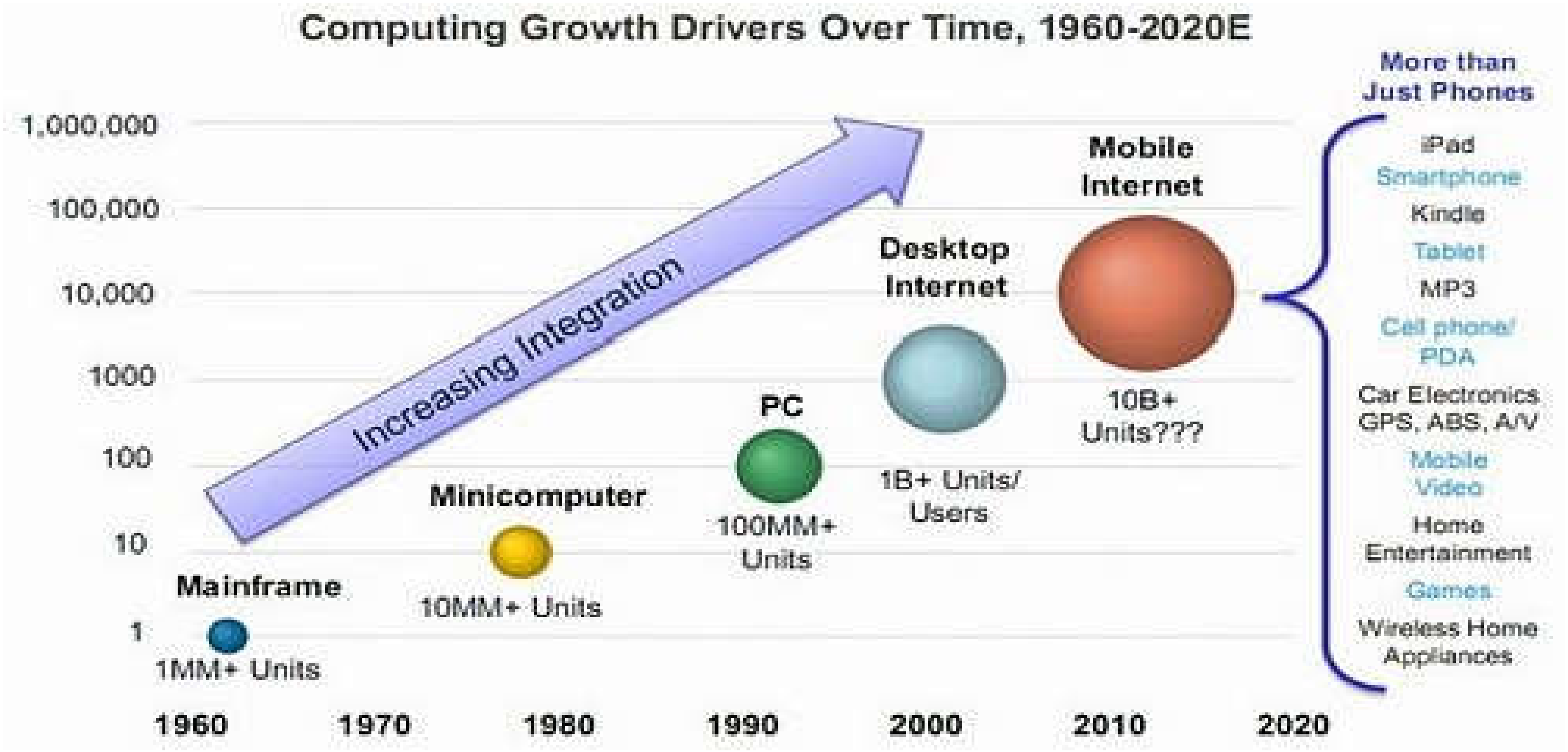
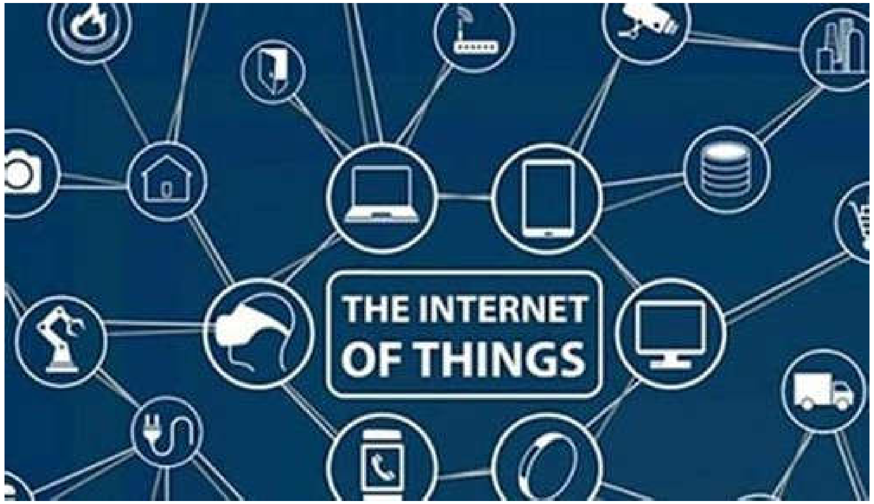
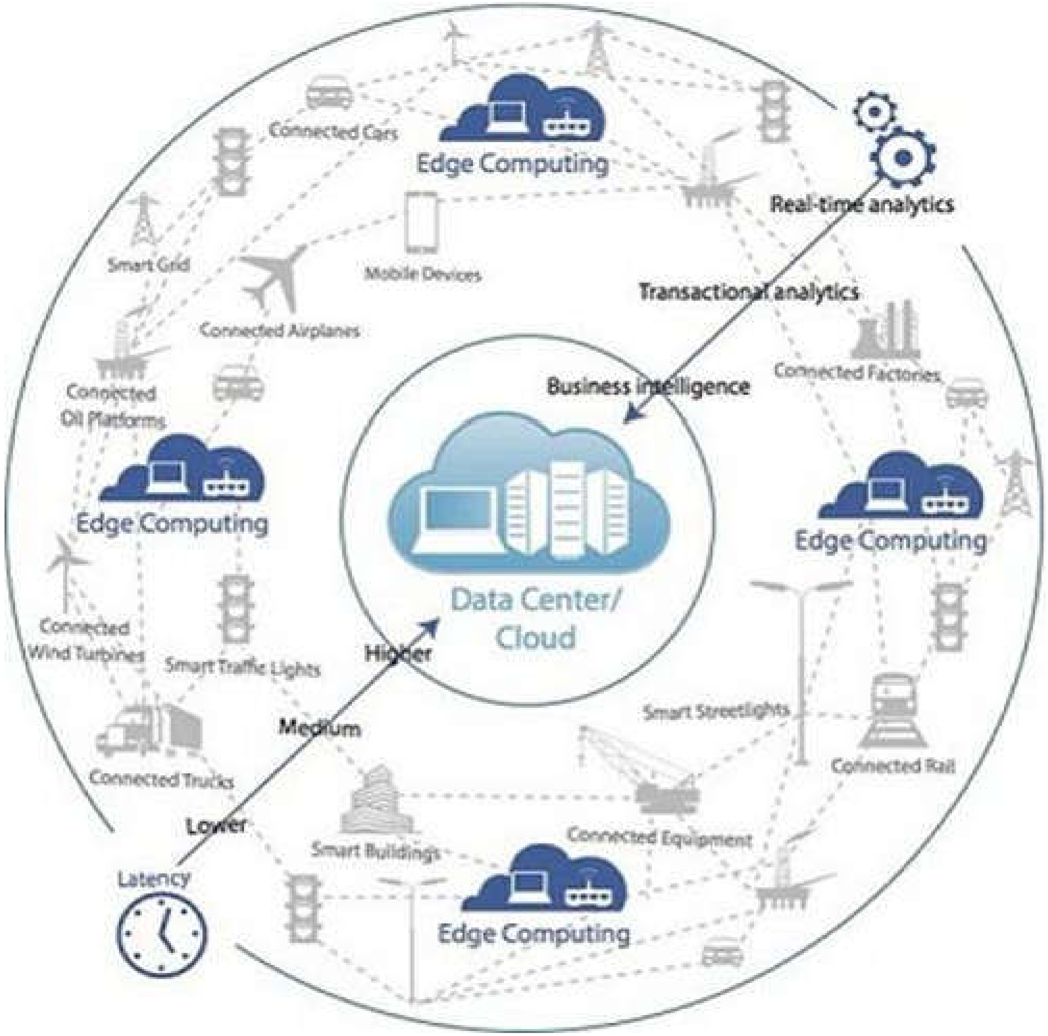
移动互联设备海量增长

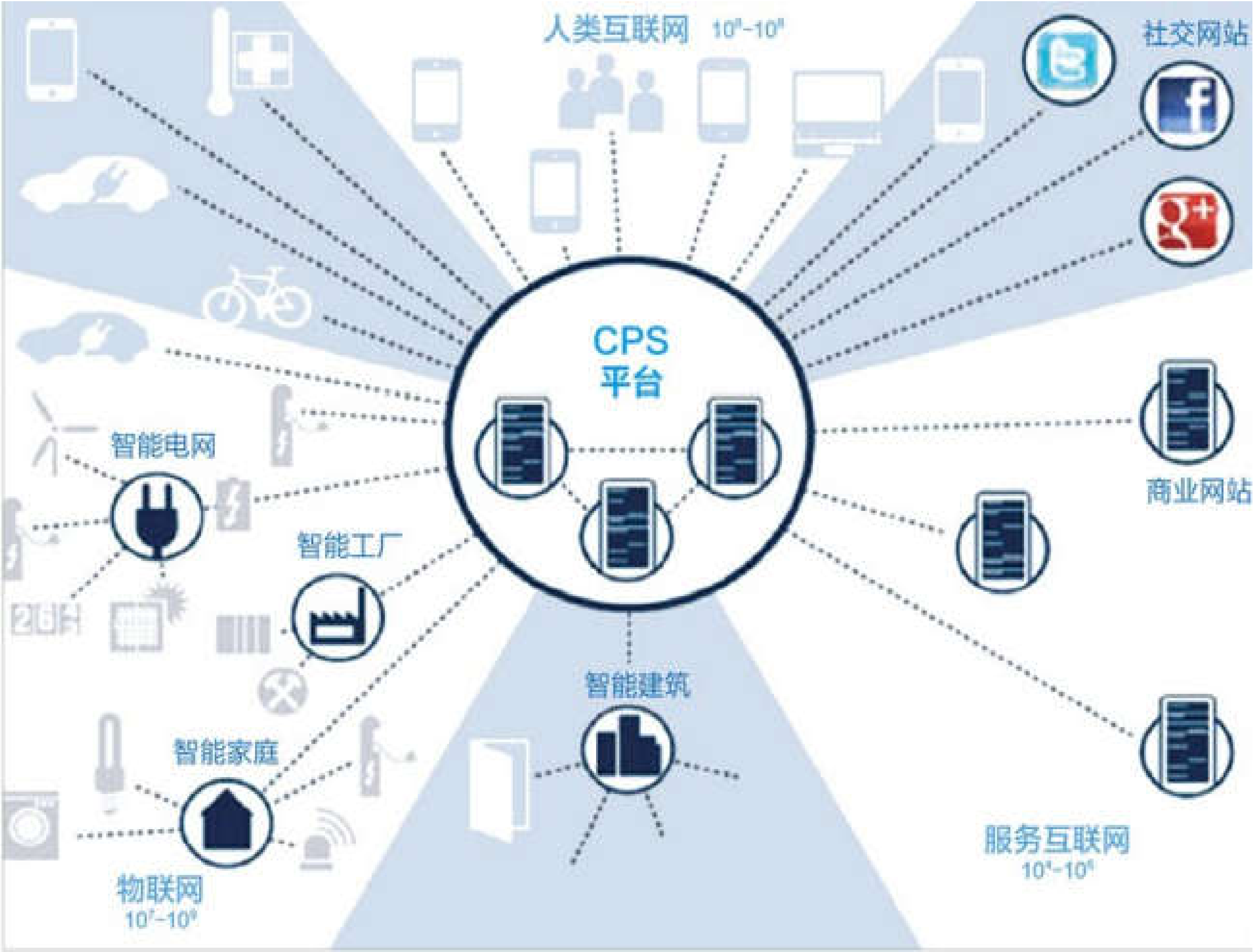

Computing Growth Drivers Over Time, 1960-2020E
1,000,000
100,000
10,000
1000
100
10
1
Increasing Integration
Mainframe
1MM+ Units
Minicomputer
10MM+ Units
PC
100MM+ Units
Desktop Internet
1B+ Units/ Users
Mobile Internet
10B+ Units???
1960
1970
1980
1990
2000
2010
2020
More than Just Phones
iPad
Smartphone
Kindle
Tablet
MP3
Cell phone/ PDA
Car Electronics GPS, ABS, A/V
Mobile Video
Home Entertainment
Games
Wireless Home Appliances

IoEverything与边缘计算


THE INTERNET
OF THINGS

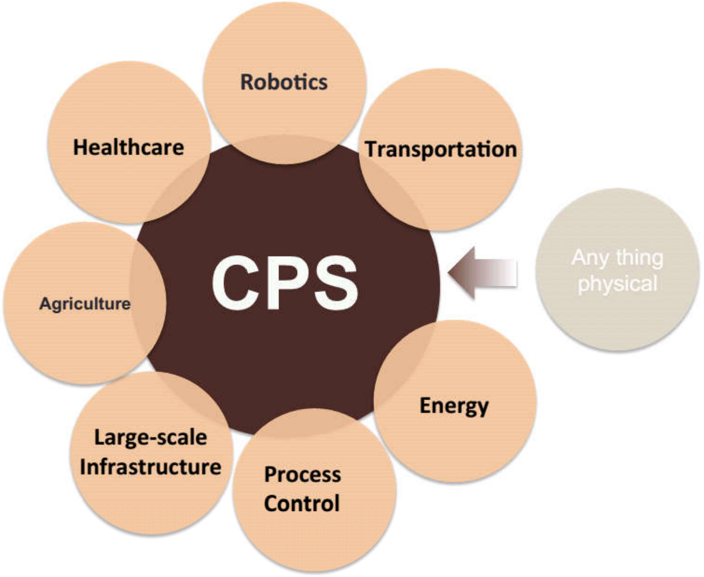

Connected Cars
Edge Computing
Real-time analytics
Smart Grid
Mobile Devices
Transactional analytics
Connected Airplanes
Connected Oil Platforms
Business intelligence
Connected Factories
Edge Computing
Edge Computing
Data Center/ Cloud
Connected Wind Turbines
Smart Traffic Lights
Higher
Medium
Smart Streetlights
Connected Rail
Connected Trucks
Lower
Smart Buildings
Connected Equipment
Latency
Edge Computing

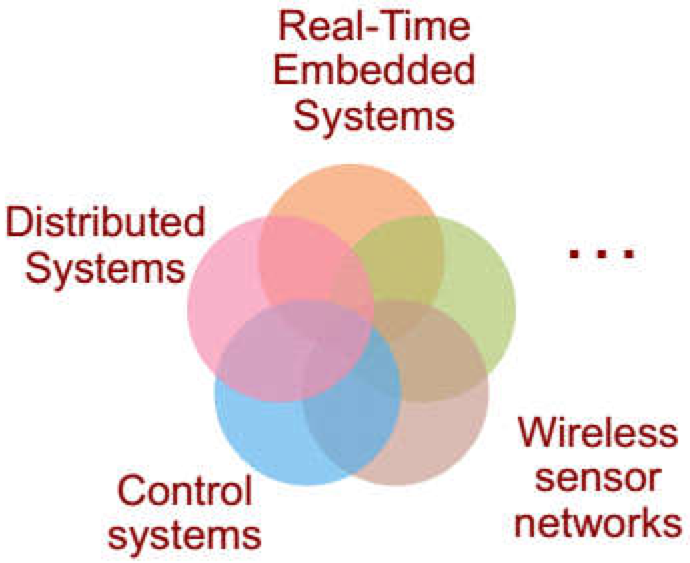
the world as we know


人类互联网 10^8-10^9
社交网站
CPS
平台
智能电网
商业网站
智能工厂
智能建筑
智能家庭
服务互联网
10^4-10^6
物联网
10^7-10^9

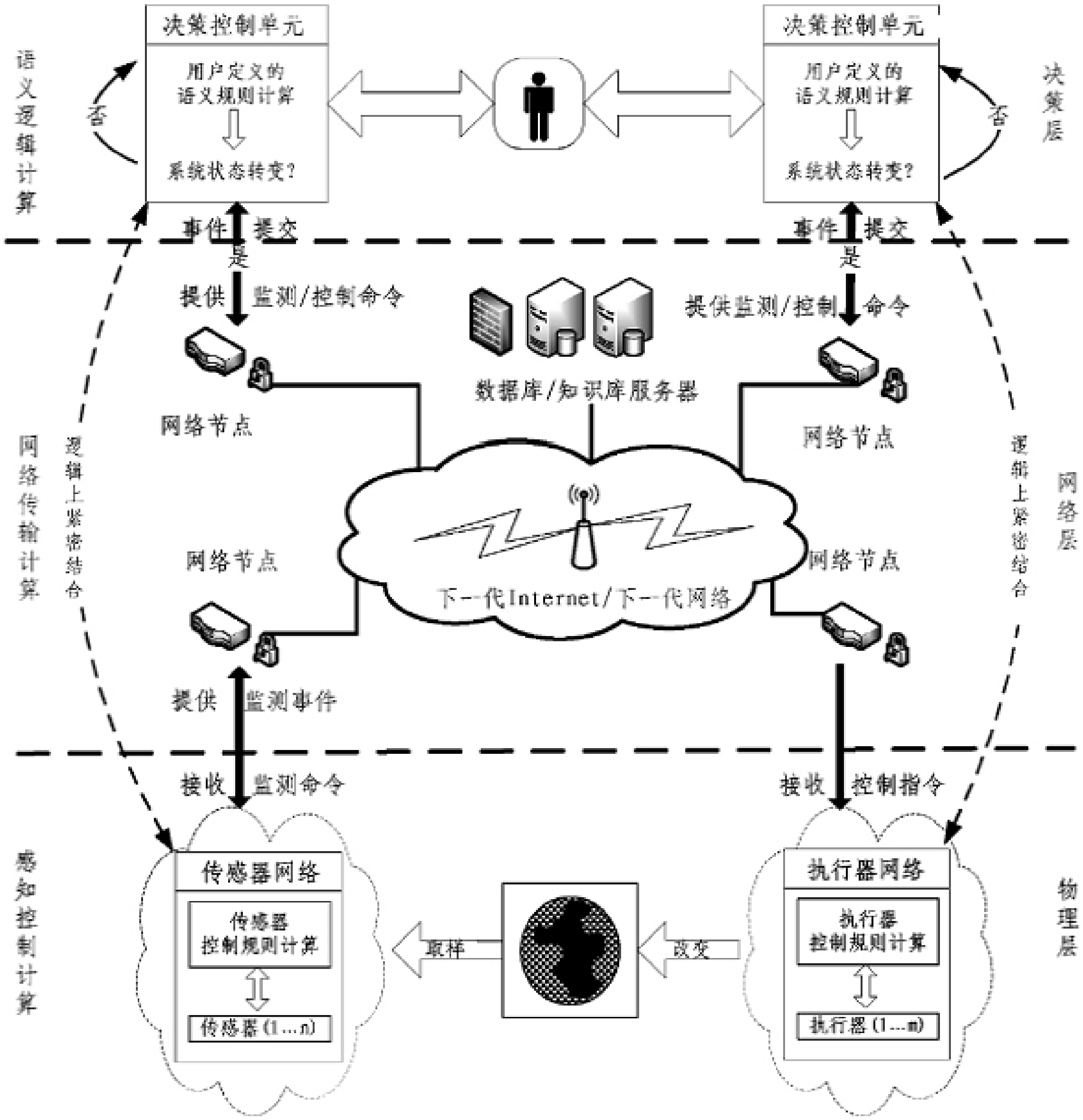
融合: Cyber-Physical Systems

- 定义
  - Physical and engineered systems whose operations are monitored, coordinated, controlled and integrated by a computing and communication core.
- 特征
  - Tight coupling (coordination) between computational and physical resources
  - Large-scale system of systems
  - Exceeds today’s systems in adaptability, autonomy, efficiency, functionality, reliability, safety, and usability
  - Convergence of computation, communication, information, and control

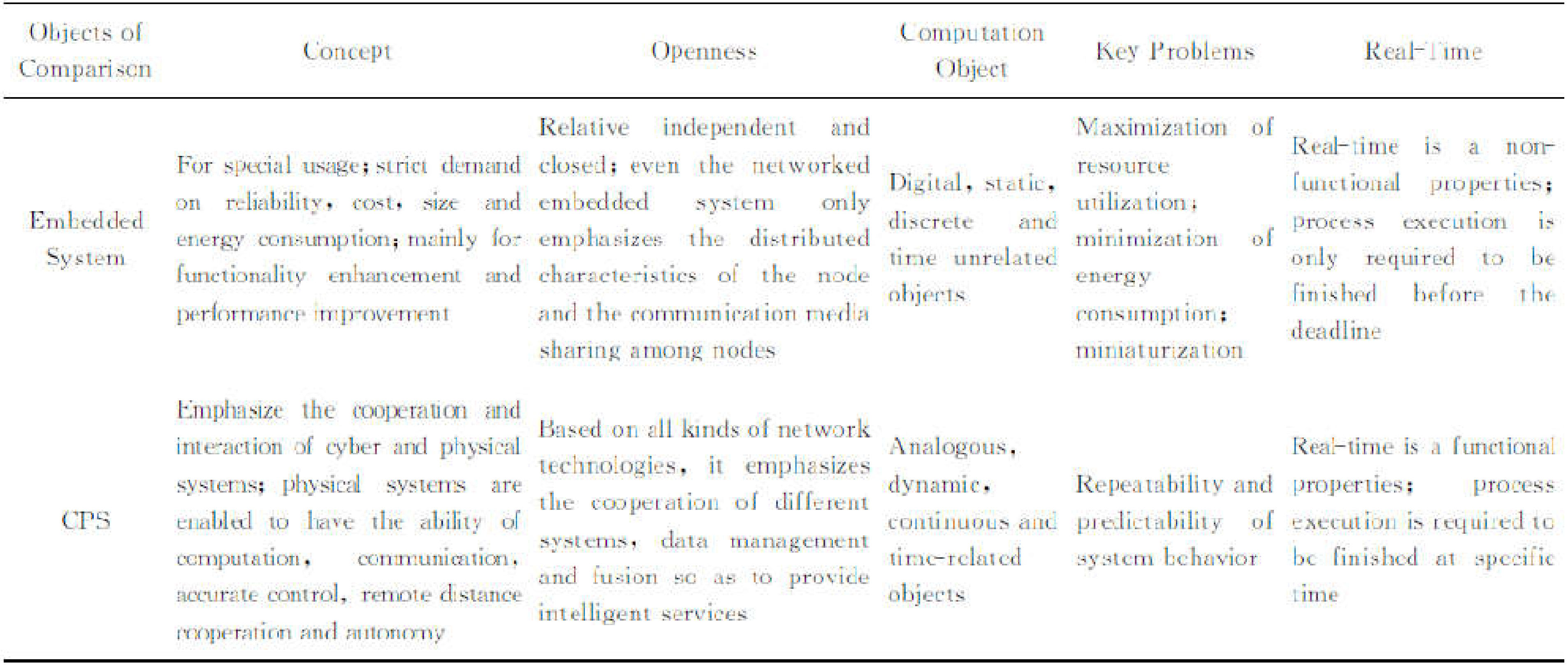

Robotics
Healthcare
Transportation
CPS
Any thing physical
Agriculture
Energy
Large-scale Infrastructure
Process Control


Real-Time Embedded Systems
Distributed Systems
. . .
Wireless sensor networks
Control systems

CPS：实时感知、动态控制、信息服务


决策控制单元
用户定义的语义规则计算
系统状态转变?
否
语义逻辑计算
决策控制单元
用户定义的语义规则计算
系统状态转变?
否
决策层
事件
提交
是
提供
监测/控制命令
提供监测/控制
命令
数据库/知识库服务器
网络节点
网络节点
网络节点
网络节点
下一代Internet/下一代网络
网络传输计算
逻辑上紧密结合
逻辑上紧密结合
网络层
提供
监测事件
接收
监测命令
接收
控制指令
感知控制计算
传感器网络
传感器控制规则计算
传感器(1…n)
取样
改变
执行器网络
执行器控制规则计算
执行器(1…m)
物理层

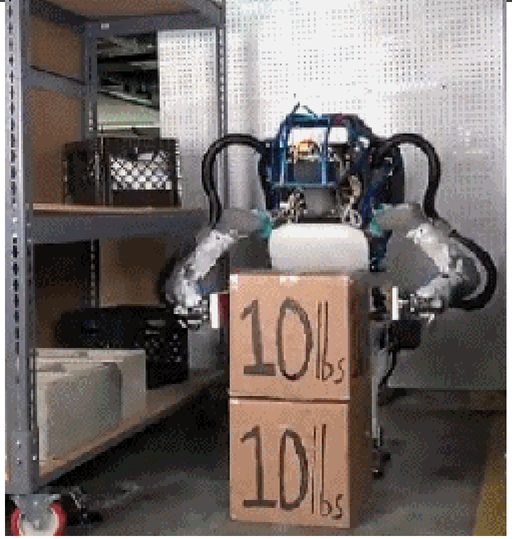
CPS与嵌入式系统的比较

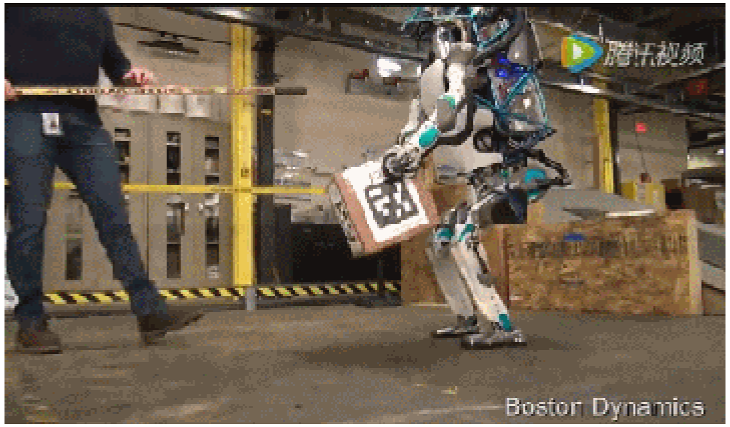


Objects of Comparison	Concept	Openness	Computation Object	Key Problems	Real-Time
Embedded System	For special usage; strict demand on reliability, cost, size and energy consumption; mainly for functionality enhancement and performance improvement	Relative independent and closed; even the networked embedded system only emphasizes the distributed characteristics of the node and the communication media sharing among nodes	Digital, static, discrete and time unrelated objects	Maximization of resource utilization; minimization of energy consumption; miniaturization	Real-time is a non-functional properties; process execution is only required to be finished before the deadline
CPS	Emphasize the cooperation and interaction of cyber and physical systems; physical systems are enabled to have the ability of computation, communication, accurate control, remote distance cooperation and autonomy	Based on all kinds of network technologies, it emphasizes the cooperation of different systems, data management and fusion so as to provide intelligent services	Analogous, dynamic, continuous and time-related objects	Repeatability and predictability of system behavior	Real-time is a functional properties; process execution is required to be finished at specific time

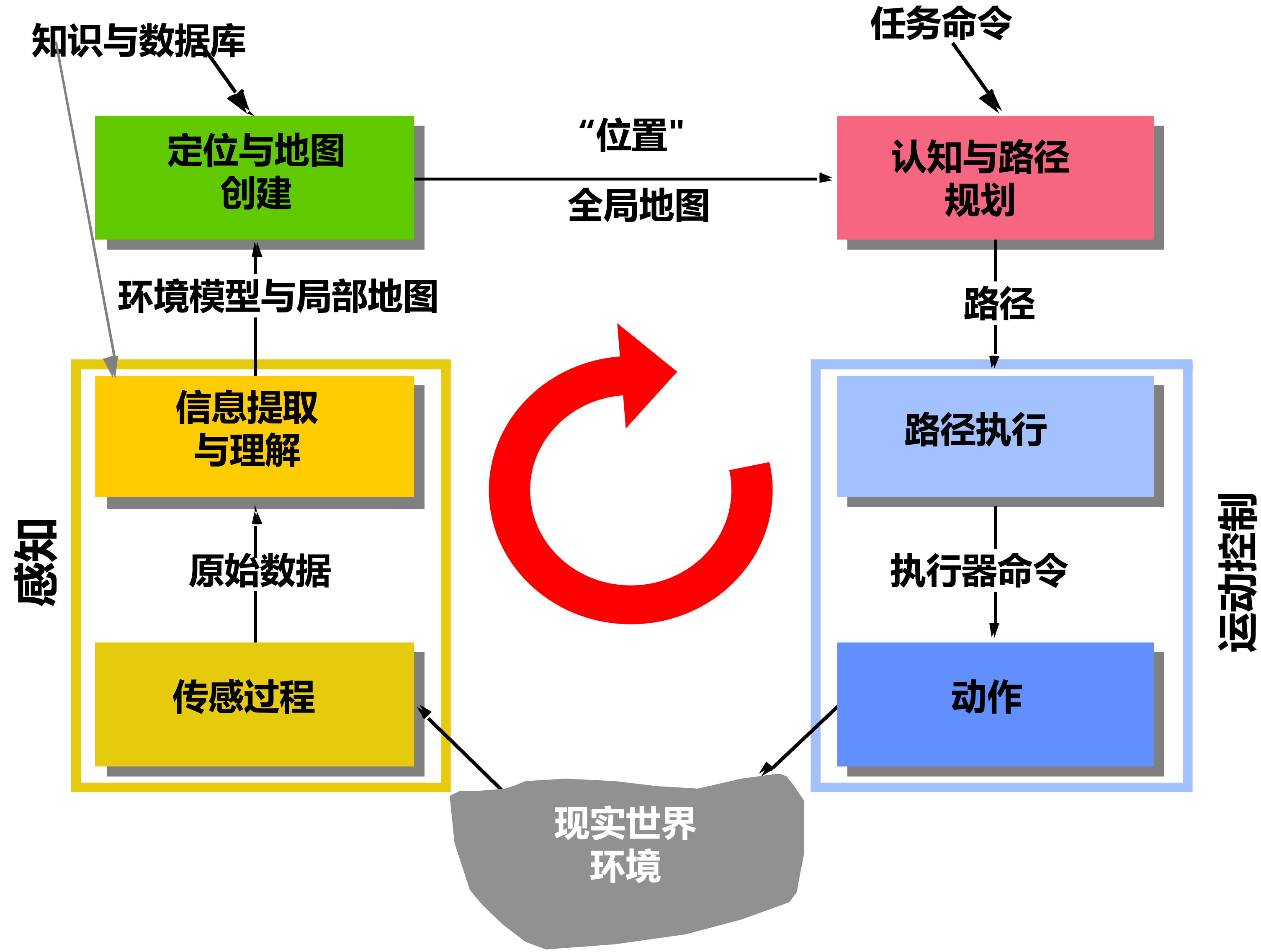
- 嵌入式设计：着重于特定应用的计算单元，而不是计算与物理单元的关联。
  - 早期：针对资源有限问题，如何优化设计？
  - 实时是非功能属性（在deadline前完成！）
- CPS：强调计算机、软件、网络、物理过程的动态融合（joint dynamics）
  - 当前：关心系统与物理过程的相互作用问题
  - 并发性是CPS固有的；实时性成为功能属性（在特定时间完成！）。

Boston Dynamics新版**Atlas**机器人


10 lbs
10 lbs


腾讯视频
Boston Dynamics

Mobile Robotics：感知、SLAM、控制



知识与数据库

定位与地图创建

“位置"

全局地图

任务命令

认知与路径规划

环境模型与局部地图

路径

信息提取与理解

原始数据

传感过程

感知

路径执行

执行器命令

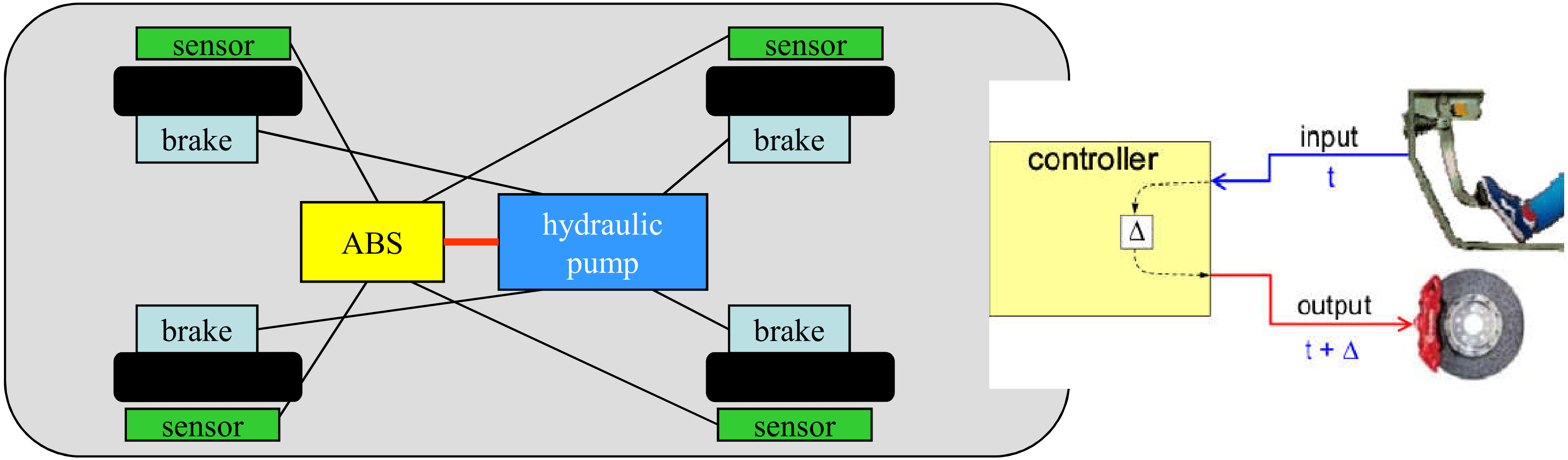
动作

运动控制

现实世界环境

汽车电子——透明的计算

- Today’s high-end automobile may have 100 microprocessors:
  - – 4-bit microcontroller checks seat belt;
  - – microcontrollers run dashboard devices;
  - – 16/32-bit microprocessor controls engine.


sensor
sensor
brake
brake
ABS
hydraulic pump
brake
brake
sensor
sensor
controller
Δ
input
t
output
t + Δ

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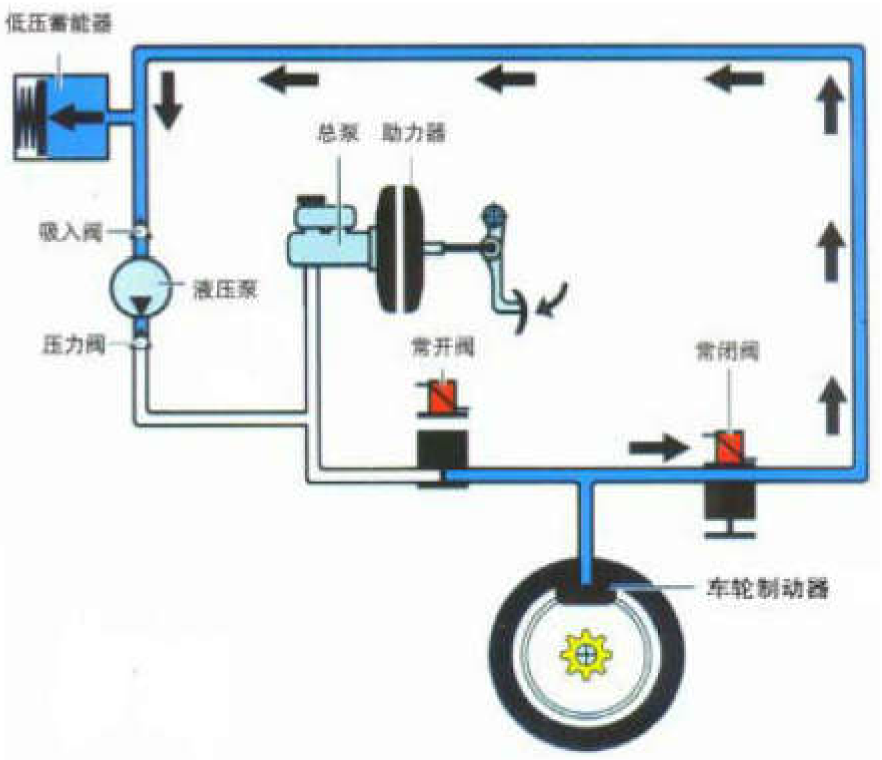
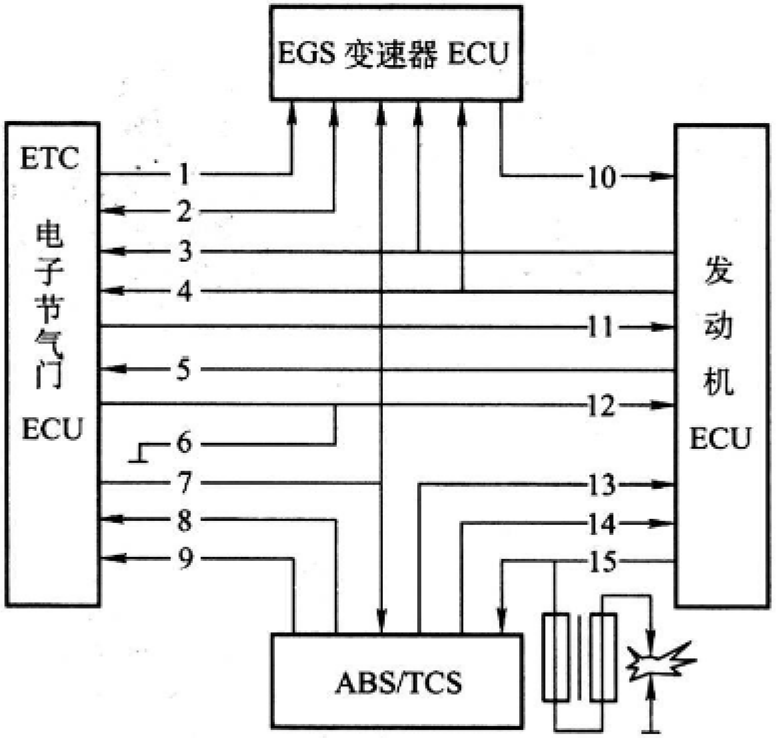
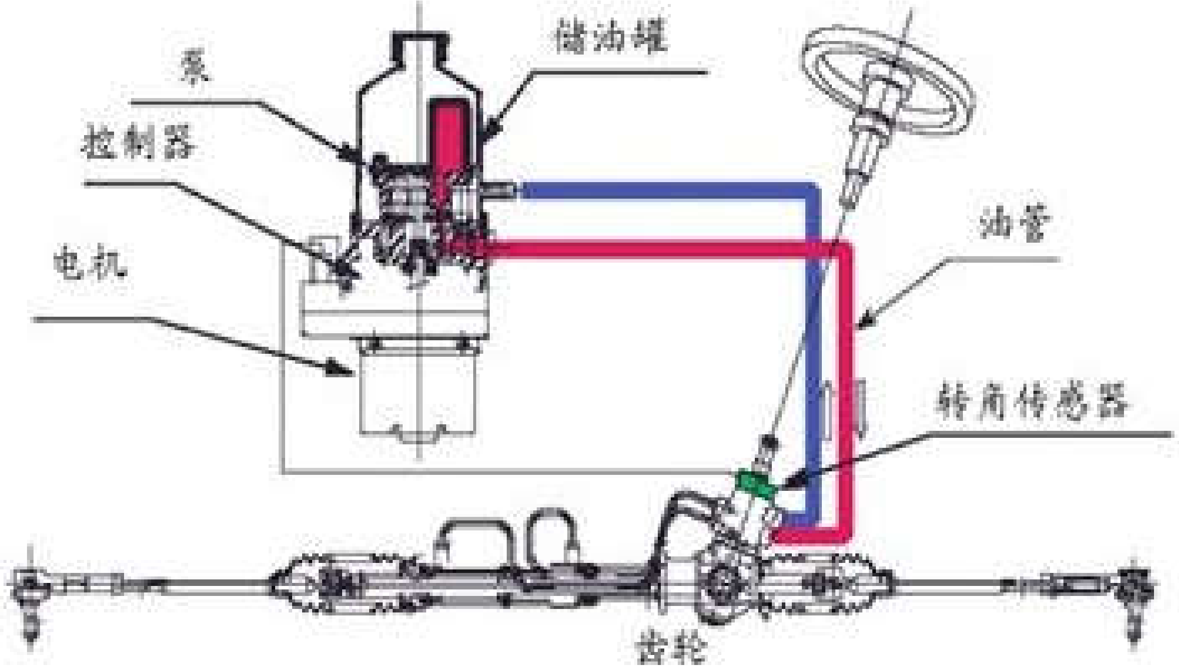
制动控制

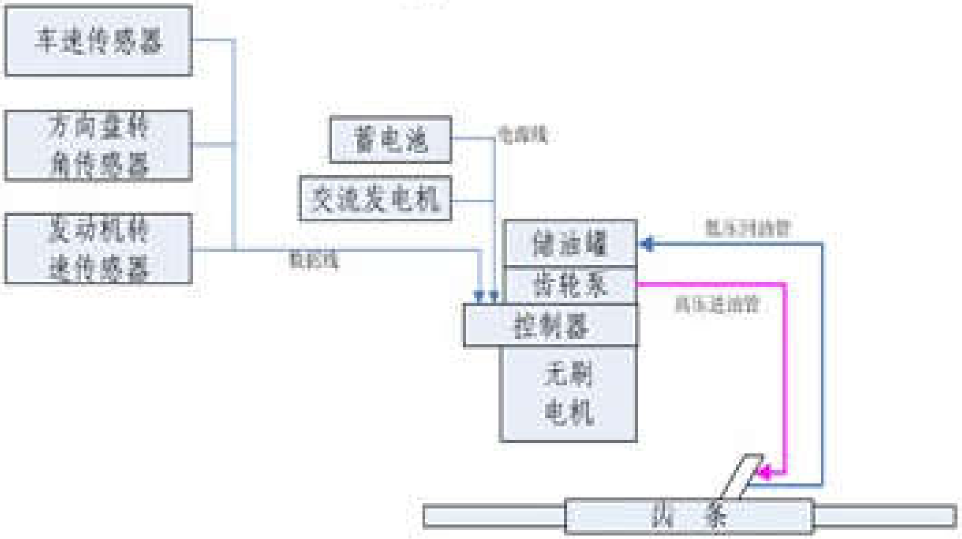

低压蓄能器
总泵
助力器
吸入阀
液压泵
压力阀
常开阀
常闭阀
车轮制动器

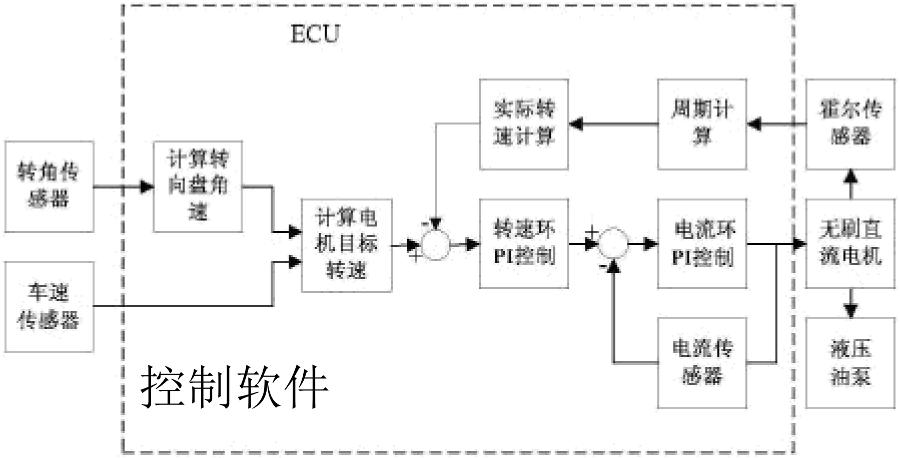

EGS 变速器 ECU
ETC
电子节气门
ECU
发动机
ECU
ABS/TCS

制动控制系统

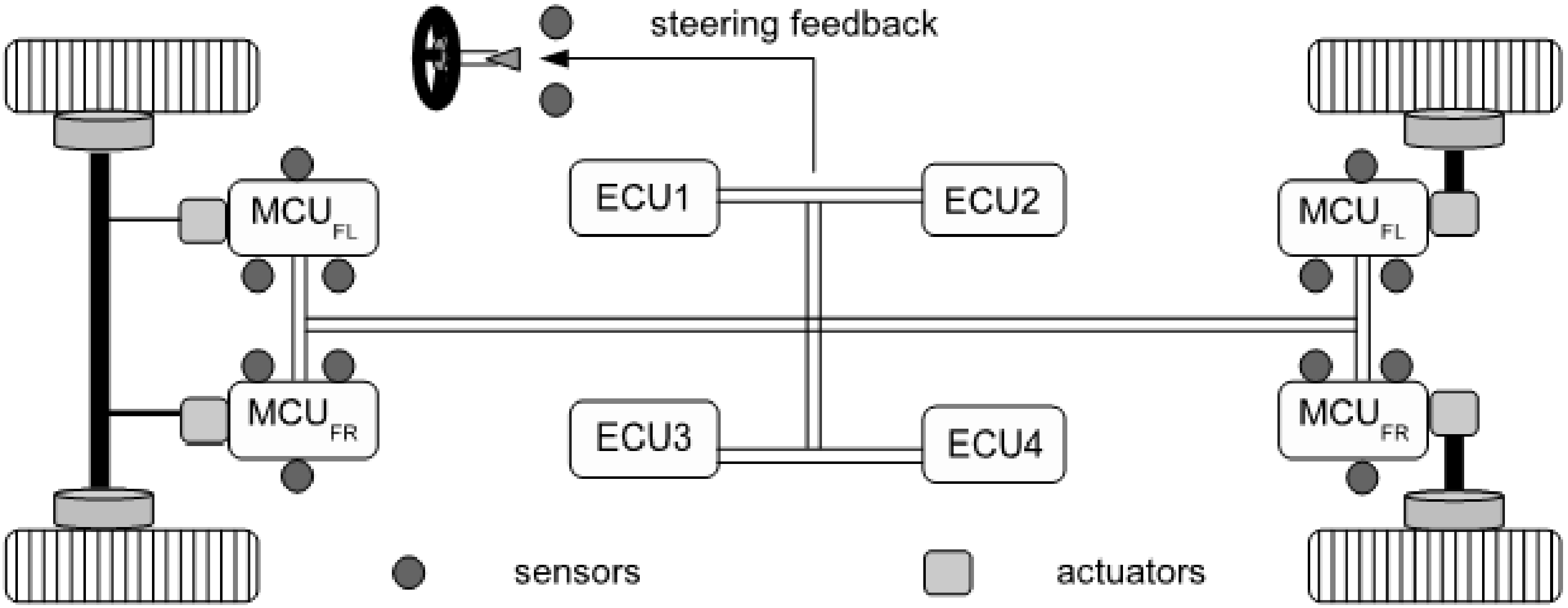
转向控制—转向助力系统


泵
储油罐
控制器
电机
油管
转角传感器
齿轮


车速传感器
方向盘转角传感器
发动机转速传感器
数据线
蓄电池
交流发电机
电源线
储油罐
齿轮泵
控制器
无刷电机
低压回油管
高压进油管
齿条


ECU
转角传感器
车速传感器
计算转向盘角速
计算电机目标转速
-
+
实际转速计算
转速环PI控制
+
-
周期计算
电流环PI控制
电流传感器
霍尔传感器
无刷直流电机
液压油泵
控制软件

STEER-BY-WIRE: FX-3 of GM


steering feedback
ECU1
ECU2
ECU3
ECU4
MCU$_{FL}$
MCU$_{FR}$
MCU$_{FL}$
MCU$_{FR}$
● sensors
▨ actuators

Sensors

Driver Interface
Desired Steer/Torque

Vehicle Interface
Wheel Angle/ Speed
Motor Current / Torque
Speed / Friction
Pitch/ Yaw/ Roll

Functionalities

Power Unit Co-ordinator

Motor Actuator Controller

Steer Feedback

Supervisiory Control

Fault Handling

Actuators

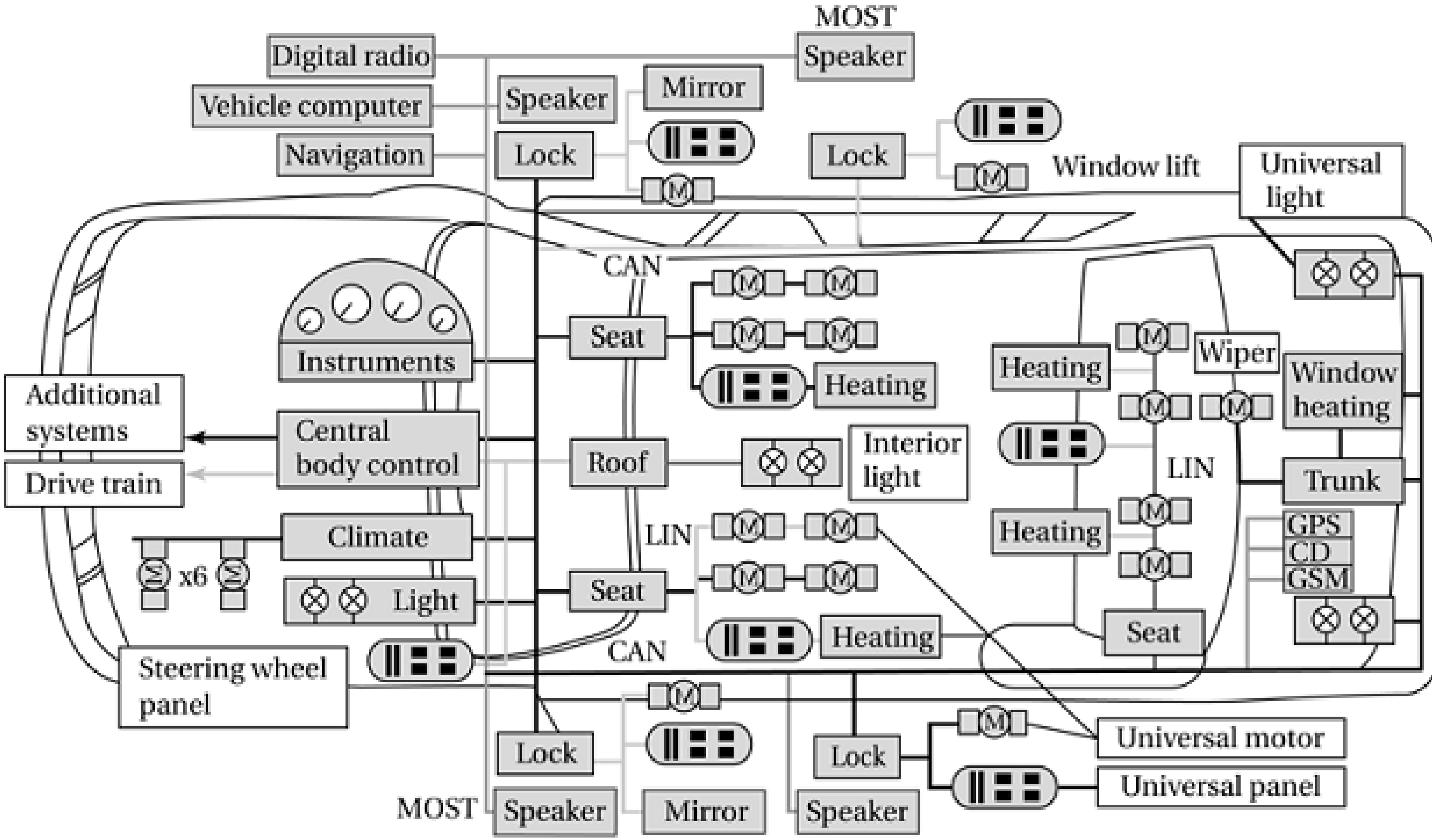
Vehicle Actuation

Wheel Motor
Actuators

Driver Feedback

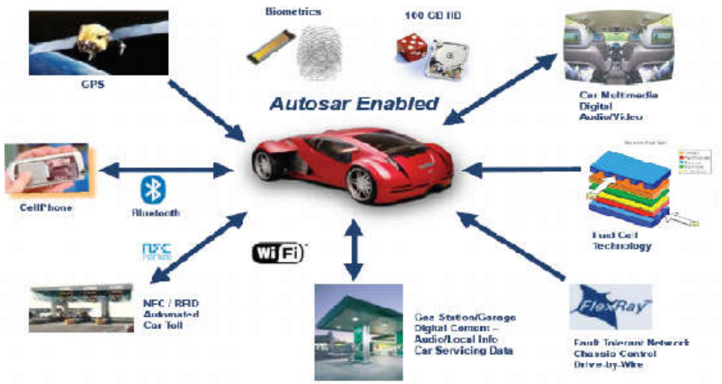
Steer Feedback
Warning

汽车总线


MOST
Digital radio
Speaker
Vehicle computer
Speaker
Mirror
Navigation
Lock
Lock
Window lift
Universal light
CAN
Instruments
Seat
Heating
Heating
Wiper
Window heating
Additional systems
Central body control
Roof
Interior light
LIN
Trunk
Drive train
Climate
LIN
Heating
GPS
CD
GSM
x6
Light
Seat
Heating
Seat
CAN
Steering wheel panel
Lock
Lock
Universal motor
Universal panel
MOST
Speaker
Mirror
Speaker

Automotive Telematics

- there are generally two distinct networks currently
  - safety-critical components
    - running of the engine
    - the brake system
    - the deployment of the airbags.
  - telematics system：non-safety-critical
    - the windshield wipers
    - the door locks
    - the cell phone
    - the entertainment systems.


GPS
Biometrics
100 GB HD
Autosar Enabled
Car Multimedia
Digital
Audio/Video
CellPhone
Bluetooth
Fuel Cell
Technology
NFC
Wi Fi
NFC / RFID
Automated
Car Toll
Gas Station/Garage
Digital Content –
Audio/Local Info
Car Servicing Data
FlexRay
Fault Tolerant Network
Chassis Control
Drive-by-Wire

- to change the car from a self-contained network (or pair of networks) into a node in a much larger network.
  - the driver of a car will be able to get on-demand directions
    - the nearest restaurant, or the closest parking space.
    - The car will be monitored, in real time, to support safe operation
    - Software upgrades
    - Emergency vehicles could be networked to traffic lights to adjust their timing and facilitate passage through crowded areas.

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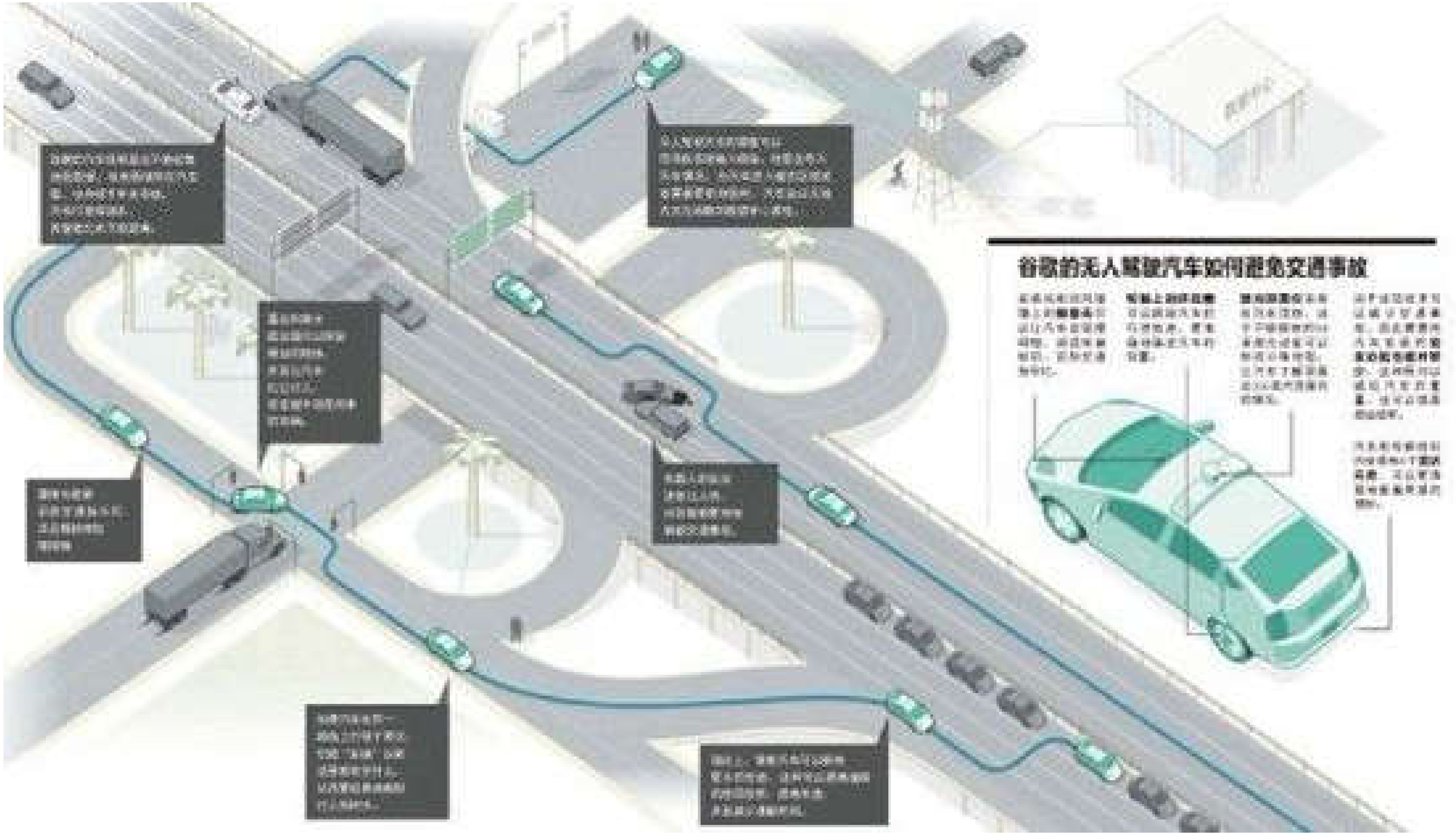
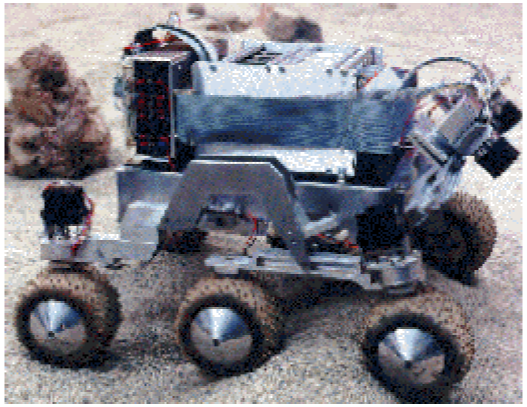
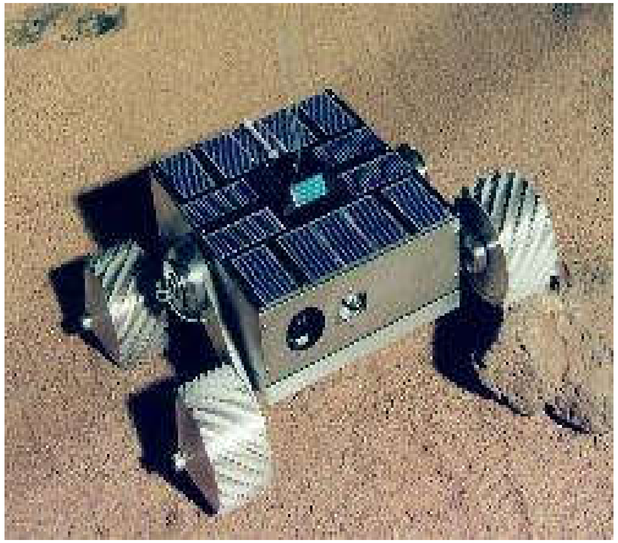
Google无人车：导航＋识别

- 基于数据驱动原理：每秒收集750Mb数据
- 通用汽车："2020年，自动驾驶系统将成为汽车标准配置"


谷歌的无人驾驶汽车如何避免交通事故

火星探路者-基于VXworks



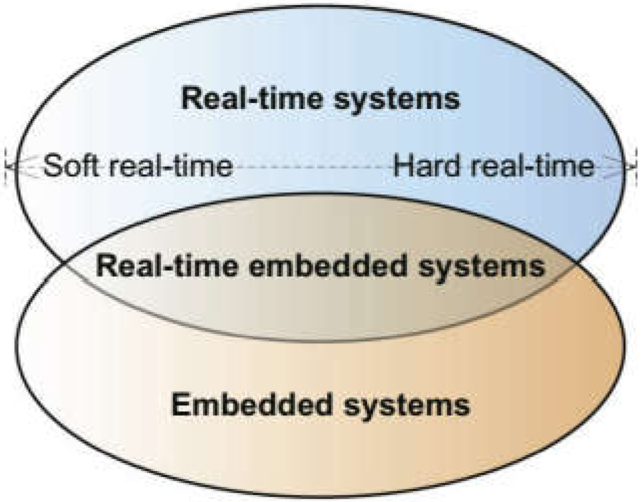


丰田意外加速事件Unintended Acceleration，2007

- 全部调查4年
  - NASA注重电子系统，没有明确给出系统存在问题的结论
  - 原告委托12位嵌入式系统专家对系统软件进行了十八个月深度审查
    - 主要动力控制系统软件源代码
    - 结论：“动力系统软件存在巨大漏洞可能导致此类事件！”
    - 一份800页13章详细报告：主要是2005年的凯美瑞
- **软件及设计错误：主要**三种缺陷
  - 非常业余的结构设计
    - 至少有67条函数复杂度超过50
      - 运行这个函数可能出现超过50种不同结果，属“非可测”级
      - 其中12条复杂度超过100，达到“非可维护”级
      - 复杂度不能超过30
    - 超过一万一千个全局变量
  - 不符合软件开发规范
    - 汽车相关软件编程规范(MISRA C)超过100条
      - 少使用全局变量，不得使用递归，。。。
  - 对关键变量缺乏保护
- 直接原因：关键任务Task X可能死亡，导致节气阀敞开！
  - 堆栈溢出：堆栈与RTOS的任务表相邻，可能造成Task X 不被调度！
  - Watchdog没有起作用

小结

- 嵌入式系统的特征
  - 通用嵌入式系统
  - 安全关键嵌入式系统（实时嵌入式系统）
- 嵌入式系统的研发涉及多领域的综合
- 当前嵌入式系统设计方法的特征
  - Top-down
  - Co-design
  - Model-based design（MBD）
  - Component-based design（CBD）
    - 功能明确单一，相互隔离，接口清晰
  - V&V


Real-time systems
Soft real-time
Hard real-time
Real-time embedded systems
Embedded systems

- 作业
  - 以某系统为例，分析其“可用性” 指标及评估方法
  - MBD设计方法的流程及要点

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Thank you