Programování systémů reálného času
Real-Time Systems Programming
*35PSR

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Czech Technical University in Prague,
FEE and CIIRC

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What is this course about?

- Real-Time operating systems (RTOS)
  - Demonstrated on VxWorks, similar for others RTOSes as well.
- Real-Time systems principles
  - What is a real-time system? HW, SW, ...
  - The aim is deterministic (predictable) behavior
  - Real-Time scheduling (theory, analysis)
  - Real-Time communication
- Safety critical systems

Literature

- J. Cooling: Real-time Operating Systems: Book 1 – The Theory, 2019
- Giorgio Buttazzo: Hard Real-Time Computing Systems, 2011
- **Jane W.S. Liu, *Real-Time Systems*, Prentice Hall, 2000**.
- Alan Burns and Andy Wellings, *Real-Time Systems and Programming Languages*, Addison Wesley, 2001

Lectures

1. Introduction to Real-Time Systems
2. VxWorks Operating System
3. POSIX 1003.1b – Standard Real-time Systems API
4. Overview of other Real-Time OSes (Linux, RTEMS, ...)
5. Introduction to safety engineering
6. Safety analysis methods (HAZOP, ...)
7. Real-Time Scheduling and Analysis (static scheduling, fixed-priority scheduling, deadline scheduling)
8. Static scheduling
9. Fixed priority scheduling
10. Dynamic priority scheduling
11. Real-Time resource management
12. Combining real-time and non-real-time tasks
13. Advanced use of C language, GCC compiler

Course grading

		Max. points
Tasks 1 – 7		35
within 1 week	5 points	
each other week	-1 points (up to -3)	
Semestral work		25
Code	18 points	
Version control	4 points	
Documentation	3 points	
Exam		40
Exam test	min 13 max 30 pt.	
Oral exam	max 10 pt.	

Authoritative information is on the course web site!

Grade	Points
A	90 – 100
B	80 – 89
C	70 – 79
D	60 – 69
E	50 – 59
F	$<$50 or $<$13 from exam test

Communication

- Website: `https://rtime.felk.cvut.cz/psr`
- E-mail: *michal.sojka@cvut.cz*
- MS Teams – ask questions that might be of interest for other students (no private emails, please)

Outline

What is a Real-Time System?

- Real-time system is a system whose specification includes both logical and temporal correctness requirements.

  Logical correctness We get correct results, e.g. $1 + 1 = 2$.

  Temporal correctness We get the results at the right time.
- Real-Time system can react in deterministic way to unpredictable events.
- The system is deterministic if the analysis of the worst-case behavior proves that all deadlines (temporal requirements) are met.
  - Techniques to verify the timing requirements are the focus of this course.
  - The question of specifying temporal requirements is important, but it is mostly out of the scope of this course. Typically, it is application specific.

Typical Characteristics of Real-Time Embedded Systems

- Event driven, reactive
- Misbehave/failure is often expensive, dangerous, life or environment threatening (safety-critical systems)
- Parallel/multithreaded programming
- Continuous operation without human interaction or supervision
- Strict demands on reliability and fault-tolerance
- Predictable behavior

Real-Time System Examples

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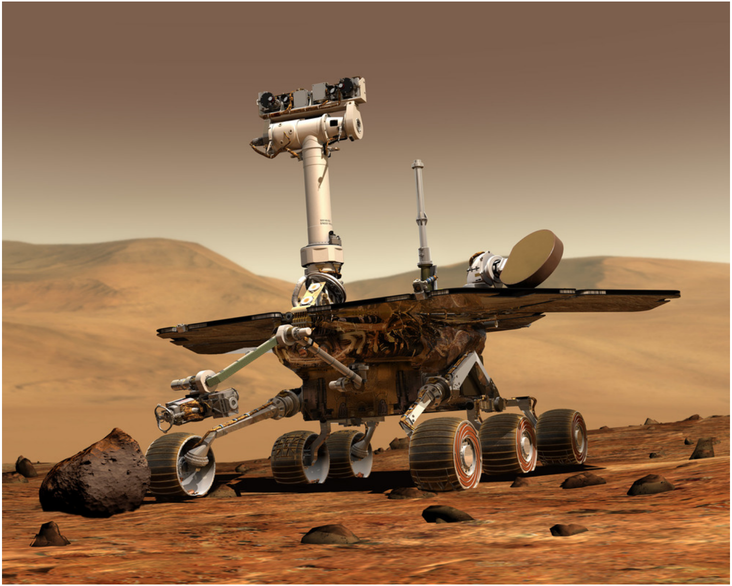
Real-Time System Examples



Real-Time System Examples

Common Misconceptions about RT Systems
(Stankovic '88)

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We will see during the course…

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No! Bad design and/or algorithms can cause infinite delays.

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May be for PR and advertising agencies.
We understand real-time as predictable.

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Deterministic timing is often more important than system throughput.

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IT people are mostly concerned about average performance.

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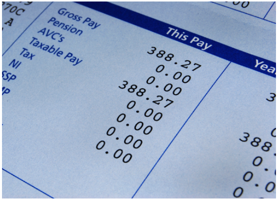
Even though everything can brake, we do not want the operating system or the application to be the weakest point in the chain.

Are All Systems Real-Time Systems?

- *Question*: Is a payroll processing system a real-time system?



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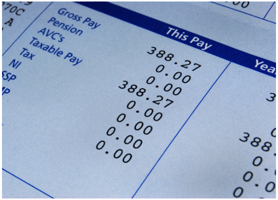

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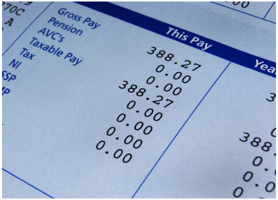

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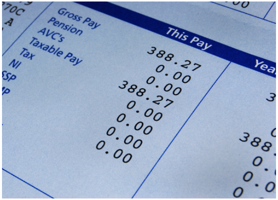
- We are interested in systems for which it is not *a priori* obvious how to meet the timing constraints.



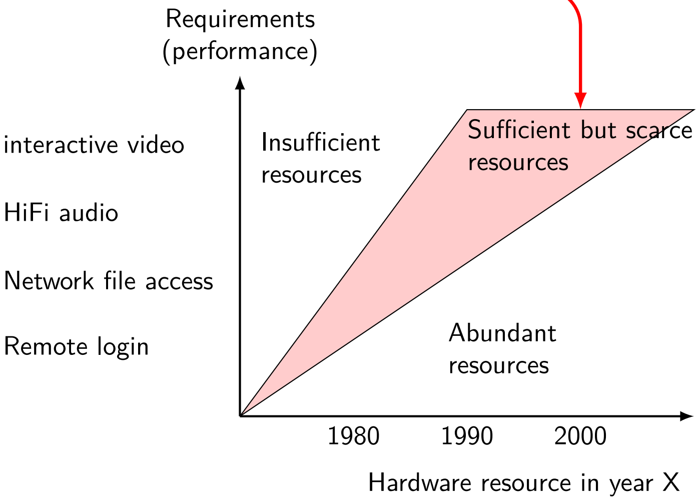
Resource Availability

Resources (CPU, memory, network, ...) may be categorized as:

- **Abundant** Almost any design methodology can be used to realize timing requirements of the application.
- **Insufficient** It is not known how to fulfill the application requirements with any known technology.
- **Sufficient but scarce** It is possible to realize the timing requirements, but careful resource allocation is required.

Example: Interactive/Multimedia Application

- Interesting RT applications are here.

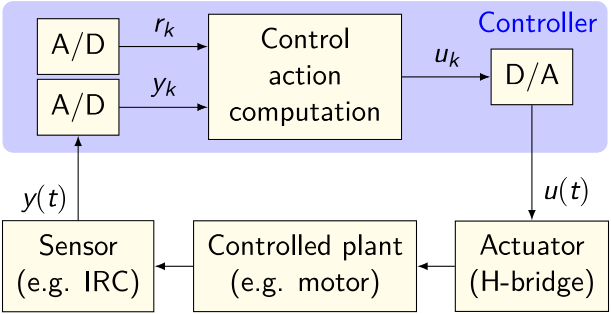


Outline

Example: Real-Time System Application

Almost each **control system** is a real-time system.

Example 1: A simple control system with one sensor and one actuator.



A simple control system (continued)

Pseudocode of a control application

Setup periodic timer to activate interrupt in each period T.
Run the next sequence for each timer interrupt activation:

- run A/D conversion and read value y
- compute controller output u
- write u and start D/A conversion

The parameter T is known as sampling frequency and the section of the proper T value depends on the dynamic properties of the controlled plant. Typical values range from one second to milliseconds or even less. Bad choice makes plant stabilization impossible or setpoint/trajectory tracking less precise than demanded.

Example: Multi-rate system

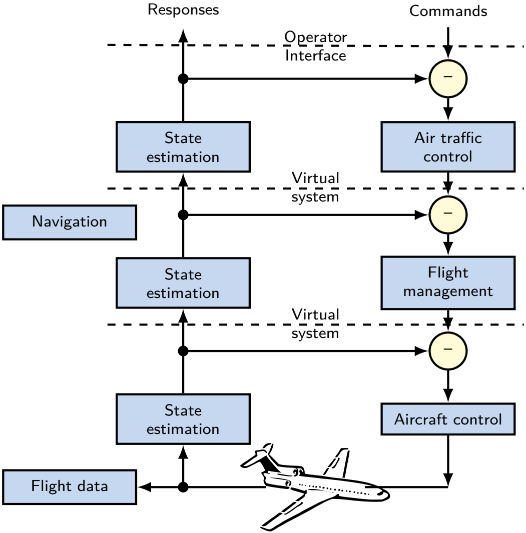
More complex control systems, multiple sensors and actuators. Different system partitions exhibit different dynamics and therefore multiple sampling periods for control loops are used.

Example 2: Helicopter control system

- Do 180× per second the following:
  - Check and read sensor data. Reconfigure (mode change) control strategy in case of sensor failure.
  - Run noise filtering and decimation on input data
  - Avionics control every 6thcycle (30 Hz):
    - Check the keyboard for the change of the control mode
    - Normalize sensor data and coordinate transformations
    - Determine reference setpoints for controllers
    - Compute outer pitch control loop control law
    - Compute outer roll control loop control law
    - Compute outer yaw and collective control loop control law.
  - Every 2ndcycle (90 Hz) run inner controller with setpoints computed in 30 Hz avionics computation):
    - Update controller output for inner pitch control loop.
    - Update controller output for inner yaw and collective control loop.
  - Update controller output for inner roll control loop.
  - Write computed control actions into outputs
  - Run internal tests
  - Wait for the next fast cycle release time

Note: Use of harmonic sampling rates simplifies the system. .

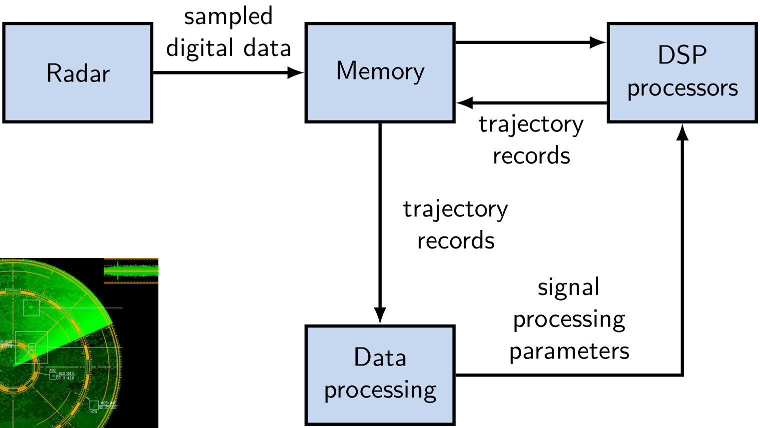
Example: Hierarchical Control System

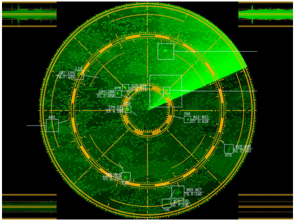


Example: Digital Signal Processing System

- Processing of a signal in different representation and conversion of the signals between these representations.
- Examples:
  - Digital filtering
  - Compression/decompression of video or audio streams
  - Radar signal processing
- Response times range from a few milliseconds to several seconds.

Example: Radar System



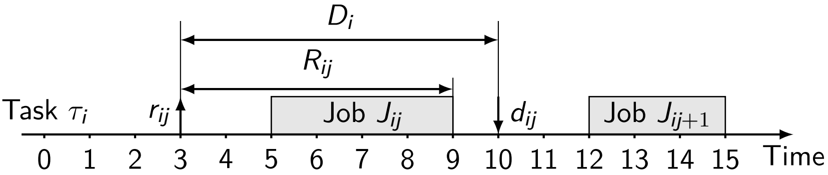


Other examples of real-time system applications I

- Multimedia
  - The typical goal is to process audio and/or video at a constant sampling frequency/framerate
  - Additional limits: Audio and video mutual synchronization, low *jitter* (discrepancy in timing), low latencies for interactive transmission (video phone)
- Real-time (industrial) databases
  - Transactions have to be committed within predefined deadline
  - **Most significant problems:** Classical algorithms for transactions scheduling and optimization aim to achieve high throughput, which is in contrast to the predictability of real-time systems.
  - Requirements for **absolute** or **relative temporal consistency**.
- Virtual reality

Outline

Basic Terminology



- ↑ = release time (r_{ij}); the job is released at time 3.
- ↓ = absolute deadline (d_{ij}); the job has to be completed before deadline; equal to 10 for this case.
- Relative deadline (D_i) is 7.
- Response time (R_{ij}) is 6.

Hard Real-Time Systems

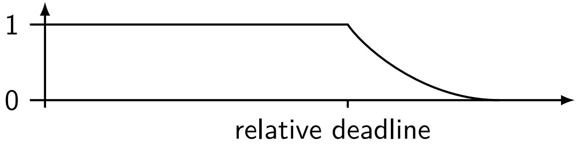
- Hard Deadline is a deadline that has to be met under all circumstances.
    - If a hard deadline is missed, the behavior of the system is wrong and it often has catastrophic consequences.
    - We need mathematical apparatus for verifying that deadlines are met.
    - But: "There is nothing like a hard deadline in the real world."
- Hard Real-Time System: is a real-time system, where all deadlines are hard.
    - This course is focused on hard real-time systems. They are easier to analyze. Why?
- **Examples:** Nuclear power plant, aircraft control.

Soft Real-Time Systems

- Soft Deadline (required completion time) can be missed occasionally.
    - **Question:** How to define the term “occasionally”?
- Soft Real-Time System: a real-time system where all deadlines are soft.
- **Example:** Multimedia applications, telephone exchanges (but what about emergency calls?).

Try to Define Term “Occasionally”

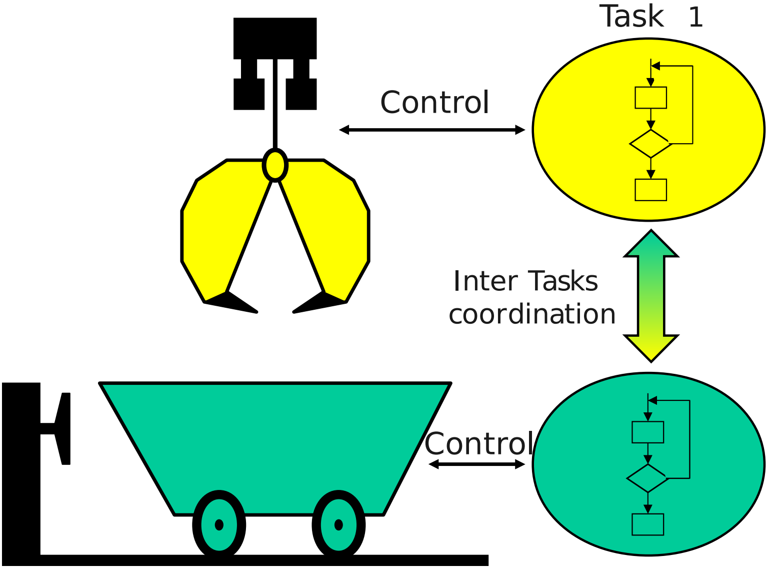
- **One approach:** Use a statistical probability model.
  - For example: 99% deadlines has to be met.
- **Another approach:** Define the function describing the outcome of a job provides as a function of its completion time.



- **Notice:** To analyze system behavior according such model is more complicated.

Outline

Parallelism in the Real World and Control Application



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  - Synchronization and data exchange between tasks represent the interaction between the elements in the real world.
  - Allows easy separation of task functions (what tasks do) and temporal characteristics (when it should be done).
  - Provide an interface (API) for application to use the hardware.
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- Real-Time OS (RTOS)
  - Similar to GPOS, but provides algorithms for real-time resource management
  - Gives timing guarantees, prevents (theoretically) unbounded latencies
  - Temporal isolation of processes (avionics)

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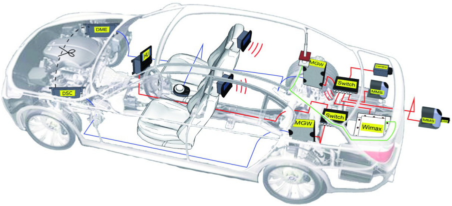
- Time resolution for measurement and task activation is fine enough

Distributed Real-Time Systems



- There are many reasons to use distributed systems
  - Increased reliability (redundancy)
  - Distribution of computational power to places where it is needed (fast local servo-control loops)
  - Simpler interconnection of subsystems from different producers (standardized communication protocols)
- Additional problems to solve: **end-to-end properties**
  - End-to-end properties (e.g. response-time) depends on more resources and components (multiple CPUs, network, ...)
  - One of the biggest challenges of today's engineers