Real-Time Systems

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Outline

1. **Introduction**
2. **Dependability issues**
3. **Scheduling issues**
4. **Fixed-priority scheduling**
5. **Task interactions and blocking**
6. **System issues**
7. **Multi-cores**
8. **Sustainability**

Bibliography

- J. Liu, "Real-Time Systems", Prentice Hall, 2000
- A. Burns, A. Wellings, "Real-Time Systems and Programming Languages (Fourth Edition): Ada 2005, Real-Time Java and Real-Time C/POSIX", Addison-Wesley, 2009

1. Introduction

Initial intuition – 1

- **Real-time system – I**
  - An aggregate of computers, I/O devices and specialized software, all characterized by
    - Intensive interaction with external environment
    - Time-dependent variations in the state of (parts of) the external environment
    - Need to keep (software) control over all individual parts of the external environment and to react to changes
  - System activities subject to timing constraints
    - Reactivity (responsiveness), accuracy, duration, completion
  - System activities are inherently concurrent
  - The satisfaction of such constraints must be proved

Initial intuition – 2

- **Real-time system – II**
  - Operational correctness does not solely depend on the logical (algorithmic, functional) result but also on the time at which the result is produced
    - The computed response has a *utility function* that depends on the application
    - Correctness is logical and temporal
  - A logically-correct response produced later than expected may be as bad a a wrong response
- **Embedded system**
  - The computer and its software are fully immersed in an engineering system comprised of the external environment subject to its control

Application requirements – 1

- A control subsystem consists of possibly distributed resources governed by an RTOS
  - *Real-time operating system*
- The RTOS design must meet critical reliability requirements
  - Measured in terms of **Maximum Acceptable Probability of Failure**
    - Typically in the range 10^{-10} to 10^{-5}

We shall return to the interpretation of this term

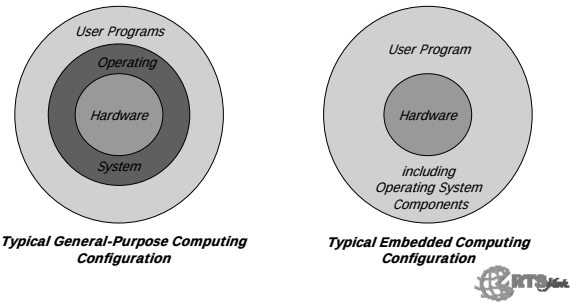
Application requirements – 2

- Safety-critical systems
  - E.g., Airbus A-320: 10^{-10} probability of failure per hour of flight
    - One failure in 10^{10} hours of flight (about 11.5 million years)
- Business-critical real-time systems
  - E.g., satellite system: between 10^{-6} and 10^{-7} probability of failure per hour of operation
    - One failure in 10^{7} hours of operation (about 11,408 years)

Real-time system

- Obligation
  - To produce logically correct results within given deadlines
- Computational correctness
  - Encompasses both **logical** and **timing** correctness
    - That is, computational correctness in both
      - ***Value domain***
      - ***Time domain***

Embedded system



Typical General-Purpose Computing Configuration

Typical Embedded Computing Configuration

Key characteristics – 1

- **Complexity**
  - Algorithmic, mostly because of the need to apply discrete control over analog and continuous physical phenomena
  - Development, mostly owing to more demanding verification and validation processes
- **Heterogeneity** of components and of processing activities
  - Multi-disciplinary (spanning control, software, and system engineering)
- Extreme **variability** in size and scope
  - From very tiny and pervasive (nano-devices) to very large (aircraft, plant)
  - In all cases, finite in computational resources
- Proven **dependability**

We shall return to the interpretation of this term

Key characteristics – 2

- Must respond to events triggered by the external environment as well as by the passing of time
  - Double nature: event-driven and clock- (or time-) driven
- Continuity of operation
  - The whole point of a real-time embedded system is that it must be capable of operating without (constant) human supervision
- Software architecture is inherently concurrent
- Must be temporally **predictable**

We shall return to the interpretation of this term

  - Need for static (off-line, preventive) verification of correct temporal behavior
    - Not easy at all

False myths – 1

- The design of real-time systems is empirical and not scientific
  - **False**: we shall see much of that in this class
- The increase in CPU power shall satisfy timing requirements coming from software of any sort
  - **False**: we continue to observe lateness all around us
- The essence of real-time computing is speed
  - **False**: we are interested in predictability, not speed
- The real-time systems discipline is no other than performance engineering
  - **False**: we shall here what it is made of

False myths – 2

- Real-time programming is low-level
  - **False**: verification is so much easier if programming is higher-level
- All real-time "problems" have long been solved in other areas of computer science
  - **False**: operation research solves (possibly similar) problems with probabilistic and/or one-shot techniques
  - **False**: general-purpose computer science more often addresses average-case optimizations

Meeting real-time requirements

- It is not sufficient to minimize the average response time of application tasks
  - "Real-time computing is not equivalent to fast computing" [Stankovic88]
- Given a set of demanding RT requirements and an implementation based on fast HW and SW, how can one show that those requirements are met?
  - Surely not only via testing and simulation
  - Maiden flight of space shuttle, 12 April 1981: 1/67 probability that a transient overload occurred during initialization; and it did, in spite of all the testing done
- **System predictability** is what we need

Predictability

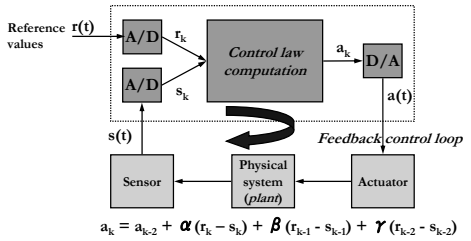
- Distinctive characteristic of a real-time system (RTS)
  - Functional and timing behavior of the system must be as **deterministic** as needed to satisfy the real-time specifications

We shall return to the interpretation of this term

- Two general dispatching paradigms for the design of **predictable** RTS
  - **Event-Triggered** (ET)
    - System activity initiated in response to the occurrence of specific events
  - **Time-Triggered** (TT)
    - System activity initiated at predefined instants of a globally synchronized clock

Example – 1

- Digital system of sensors and actuators

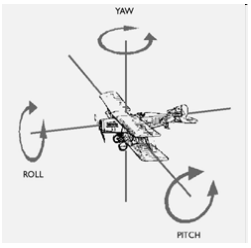


$a_k = a_{k-2} + \alpha (r_k - s_k) + \beta (r_{k-1} - s_{k-1}) + \gamma (r_{k-2} - s_{k-2})$

Example – 2

- Factors of influence
  - Quality of **responsiveness**
    - Sensor sampling is typically periodic (for convenience)
    - Actuator commanding is produced at the time of the next sampling
      - As part of feedback control mathematics
    - System stability degrades with the width of the sampling period
  - Plant **capacity**
    - Good-quality control reduces oscillations
    - A system that needs to react rapidly to environmental changes and is capable of it within ***rise time*** R requires higher frequency of actuation and thus faster sampling hence shorter ***period*** T
    - A "good" R/T ratio ranges [10 .. 20]

Example – 3



- Complex systems must support multiple distinct periods T_i
  - It is convenient to set a **harmonic** relation between all T_i
    - This removes the need for concurrency of execution in the relevant computations
    - But it causes coupling between possibly unrelated control actions which is a poor architectural choice
  - There may for example be diverse components of speed
    - *Forward, side slip, altitude*
  - As well as diverse components of rotation
    - *Roll, pitch, yaw*
  - Each of them in principle requires a score of separate control activities each performed at a specific rate

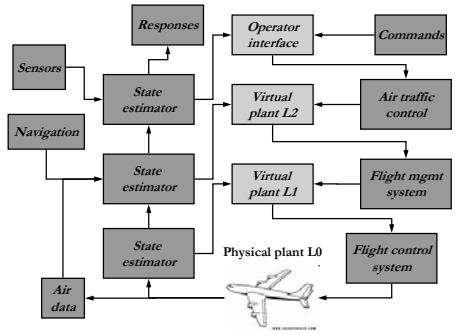
Example – 4

- Flight control system *harmonic multi-rate* functions
  - 180 Hz cycle
    - Check all sensor data and select sources to sample
      - In case of read error: reconfigure system
    - 30 Hz cycle (at every 6th activation)
      - Capture operator keyboard input and choice of operation model
      - Normalize sensor data and transform coordinates
      - Update reference data
    - 30 Hz cycle (at every 6th activation)
      - Perform control law for pitch, roll, yaw (external loop)
      - Perform integration
    - 90 Hz cycle (at every 2nd activation)
      - Perform control law for pitch, roll, yaw (internal loop)
    - Perform control law yaw (internal loop) on outputs of 90 Hz cycle
    - Command actuators
    - Perform sanity check

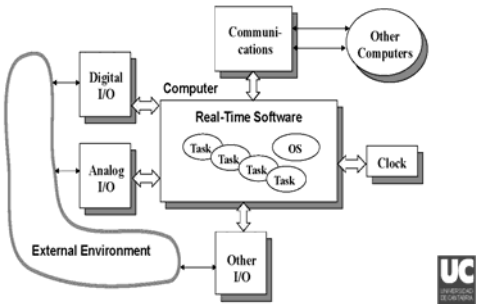
Example– 5

- Command and control systems are often organized in a hierarchical fashion
  - At the lowest level we place the digital control systems that operate on the physical environment
  - At the highest level we place the interface with the human operator
    - The output of high-level controller becomes a reference value **r(t)** for some low-level controller
  - The more composite the hierarchy the more complex the interdependence in the logic and timing of operation

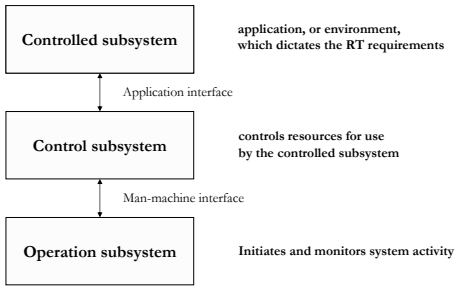
Example – 6



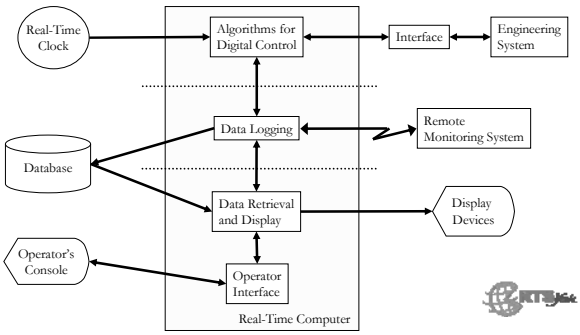
An overall vision



A conceptual model



A typical embedded system



An initial taxonomy – 1

- The prevailing classification stems from the traditional standpoint of control algorithms
  - Strictly periodic systems
    - Harmonic multi-rate (artificially harmonized)
    - Polling for not-periodic events
  - Predominantly (but not exclusively) periodic systems
    - Lower coupling
    - Better responsiveness to not-periodic events
  - Predominantly not-periodic systems but still predictable
    - Events arrive at variable times but within bounded intervals
  - Not-periodic and unpredictable systems

An initial taxonomy – 2

- **Periodic** tasks
  - Their jobs become ready at regular interval of time
  - Their arrival is synchronous to some time reference
- **Aperiodic** tasks
  - Recurrent but irregular
  - Their arrival cannot be anticipated (asynchronous)
- **Sporadic** tasks
  - Their jobs become ready at variable times but at bounded minimum distance from one another

Some terminology

- Time-aware
  - A system that makes explicit reference to time
    - E.g., open vault door at 9.00 AM
- Reactive
  - A system that must produce outputs within deadlines relative to inputs
    - Control systems are reactive by nature
    - Hence required to constrain the time variability (***jitter***) of their input and output
      - Input jitter and output jitter control

Definitions – 2

- **Release time**
  - When a job should become eligible for execution
    - The corresponding trigger is called *release event*
    - There may be some temporal delay between the arrival of the release event and when the scheduler actually recognizes the job as ready
  - May be set at some offset from the system start time
    - The offset of the first job of task `T` is named *phase* and it is an attribute of `T`

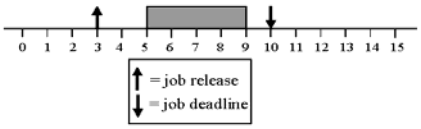
Definitions – 1

- **Job**
  - Unit of work selected for execution by the scheduler
  - Needs physical and logical resources to execute
  - Each job has an entry point where it awaits activation
- **Task**
  - Unit of functional and architectural composition
  - Issues jobs (one at a time) to perform actual work
    - One such task is said to be *recurrent*

Definitions – 3

- **Deadline**
  - The time by which a job must complete its execution
    - For example, by the next release time
  - In general it is a fully arbitrary value and may be <, =, > than the job's next release time
- **Response time**
  - The span of time between the job's release time and its actual completion
  - The longest admissible response time for a job is termed the job's *relative deadline*
  - The algebraic summation of release time and relative deadline is termed *absolute deadline*

Example



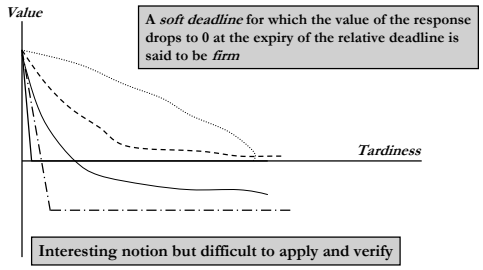
Job is released at time 3.
It's (absolute) deadline is at time 10.
It's relative deadline is 7.
It's response time is 6.

Jim Anderson Real-Time Systems Introduction - 18

Definitions – 4

- **Hard deadline**
  - If the consequences of a job completing past the deadline are intolerable
    - Satisfaction must be validated
- **Soft deadline**
  - If the consequences of a job completing past the assigned deadline are tolerable as long as the violation event is occasional
    - The quantitative interpretation of "occasional" may be established in either probabilistic terms (x% of times) or as a *utility function*
- **Tardiness**
  - The temporal distance between a job's response time and its deadline
    - Evaluates to 0 for all completions within deadline
- **Usefulness**
  - Value of utility of the job's computation product as a function of its tardiness
  - Normally associated to the notion of *laxity*

Utility function



A *soft deadline* for which the value of the response drops to 0 at the expiry of the relative deadline is said to be *firm*

Interesting notion but difficult to apply and verify

An initial taxonomy – 3

- According to timing requirements
  - **Hard real-time** (HRT) tasks
    - Whose jobs have hard deadlines
  - **Soft real-time** (SRT) tasks
    - Whose jobs have soft deadlines
  - **Firm real-time** (FRT) tasks
    - Whose jobs have soft deadlines but with null utility past deadline
  - **Not real-time** tasks
    - Do not exhibit timing requirements

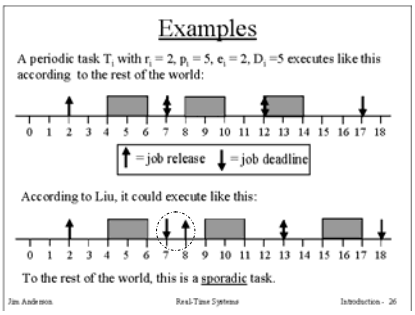
Classes of real-time systems

- HRT systems
  - Subclass of real-time systems in which all, most or some (not isolated) tasks have hard deadlines
- SRT systems
  - Subclass of real-time systems in which no deadlines are hard
- FRT systems
  - Equivalent to SRT except that there is no benefit from late delivery of service
- Actual systems often are mixed in nature
  - Which class do they belong in then?

Abstract models – 1

- Resources
  - Active (*processor*, *server*)
  - Passive (memory, shared data, semaphores, …)
    - May be reused if use does not exhaust them
    - If always available in sufficient quantity to satisfy all requests they are said to be *plentiful* and are excluded from the space of the problem
- Temporal parameters
  - **[Release-time] Jitter**
    - Possible variability in the release time
  - **Inter-arrival time**
    - Separation time between the release time of successive jobs that are not strictly periodic
      - **Sporadic job** if a guaranteed minimum value exists
      - **Aperiodic job** otherwise

Periodic task and sporadic task



Abstract models – 2

- Execution time
  - May not be constant and can vary between a *best-case execution time* (BCET) and a *worst-case execution time* (WCET)
- **Periodic model**
  - Comprised of periodic and sporadic jobs
  - Accuracy of representation decreases with increasing jitter and variability of execution time
  - *Hyperperiod* H of task set $\{Ti\}_{i=1,..,N}$
    - LCM (least common multiple) of periods {Pi}
  - *Utilization*
    - For every task Ti : ratio between ET and period : Ui = Ei / Pi
    - For the system (***total utilization***) : $\sum$i Ui

Abstract models – 3

- Fixing execution parameters
  - The time that elapses between when a periodic job becomes ready and the next period P is certainly < P
  - Setting phase > 0 and deadline D < P for a job may help limit jitter in its response time
  - The jobs of a system may be independent of one another
    - Hence they can execute in any order
  - Else they may be subject to *precedence constraints*
    - As it is typically the case in collaborative architectural styles
      - E.g., *producer – consumer*

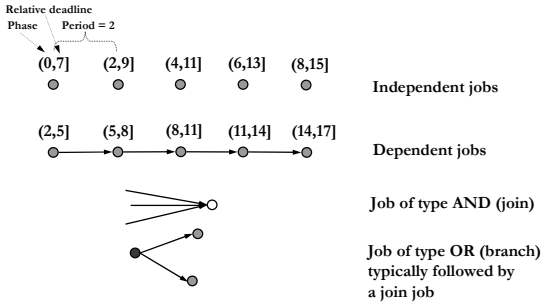
Abstract models – 4

- Fixing functional parameters
  - Permissibility of job preemption
    - May depend on the capabilities of the execution environment
    - But also on the programming style
      - *Non-reentrancy*
    - Preemption incurs non-null time overhead
  - Job *criticality*
    - May be assimilated to a priority of execution eligibility
    - In general indicates which activities must be guaranteed even possibly at the cost of others
  - Permissibility of resource preemption
    - Some resources are intrinsically preemptable (luckily! Which ones?)
    - Others do not permit it
      - Which becomes one of the four preconditions to deadlock

Abstract models – 5

- Selecting job for execution
  - The scheduler assigns a job to the processor resource
  - The resulting assignment is termed *schedule*
  - A schedule is ***valid*** if
    1. Each processor is assigned to at most 1 job at a time
    2. Each job is assigned to at most 1 processor at a time
    3. No job is scheduled before its release time
    4. The scheduling algorithm ensures that the amount of processor time assigned to a job is no less than its BCET and no more than its WCET
    5. All precedence constraints in place among tasks as well as among resources are satisfied

Extended precedence graphs (task graphs)



Abstract models – 6

- A valid schedule is said to be *feasible*
  - If the temporal constraints of every job are all satisfied
- A job set is said to be *schedulable* by a scheduling algorithm
  - If that algorithm always produces a valid schedule for that problem
- A scheduling algorithm is *optimal*
  - If it always produces a feasible schedule when one exists
- In an actual system there may be multiple schedulers that operate in some hierarchical fashion
  - Some scheduler governs access to logical resources
  - Some other schedulers govern access to physical resources

Abstract model – 7

- Two algorithms are of prime interests for real-time systems
  - The scheduling algorithm, which we should like it was optimal
    - Comparatively easy problem
  - The algorithm to compute **feasibility analysis**
    - Much harder problem
- The scientific community, but not always in full consistency, divides the latter in
  - **Feasibility tests**, which are exact
    - Necessary and sufficient
  - **Schedulability tests**, which are only sufficient

Further characterization – 1

	Time-Share Systems	Real-Time Systems
Capacity	High throughput	Ability to meet timing requirements: Schedulability
Responsiveness	Fast average response	Ensured worst-case latency
Overload	Fairness	Stability of critical part

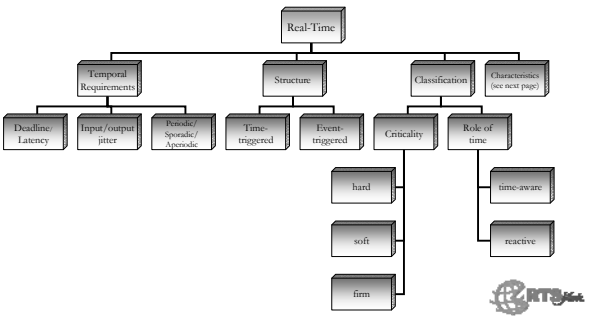
Further characterization – 2

- The design and development of a RTS are concerned with the worst case as opposed to the average case
  - Improving the average case is of no use and it may even be counterproductive
    - The cache addresses the average case and therefore operates according to a counterproductive principle for real-time systems
- Stability of control prevails over fairness
  - The former concern is selective the other general
- When feasibility is proven, starvation is of no consequence
  - The non-critical part of the system may even experience starvation

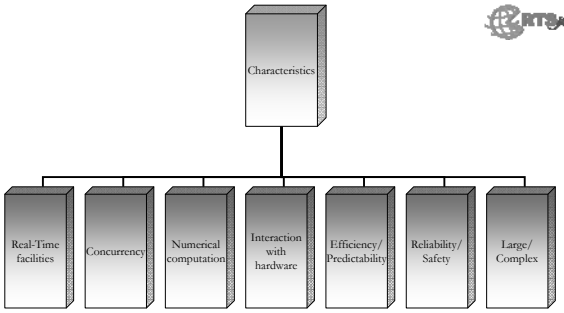
Summary – 1

- From initial intuition to more solid definition of real-time embedded system
- Survey of application requirements and key characteristics
- Taxonomy of tasks
- Dispelling false myths
- Introduced abstract models to reason in general about real-time systems

Summary – 2



Summary – 3


Characteristics
Real-Time facilities
Concurrency
Numerical computation
Interaction with hardware
Efficiency/ Predictability
Reliability/ Safety
Large/ Complex