Reference model of real-time systems

Chapter 3 of Liu

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September 20, 2022

Some slides are derived from lectures by Steve Goddard and James H. Anderson

Reference model of RT systems

In order to analyze a RT system/application, it is necessary to create its model.

Main parts of RT system models

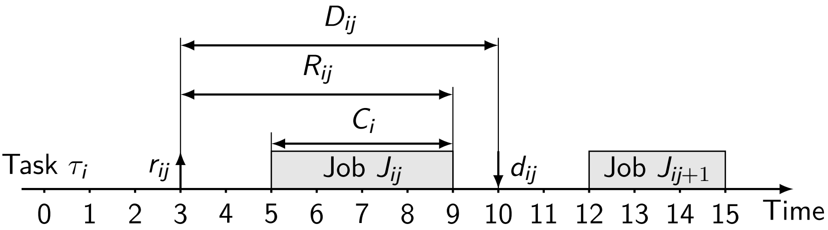
- Workload model describes the applications in the system.
- Resource model describes available system resources.
- Algorithms that define how the system resources are used.

Outline

Real-Time Applications Categories

- Purely periodic
  - Every task is released periodically
  - Constant or almost constant demand for system resources
  - **Examples:** digital controller, flight control, real-time monitoring
- Mostly periodic
  - Most of the tasks are released periodically
  - System has to respond to external asynchronous events
  - **Examples:** modern avionics or control systems
- Asynchronous and predictable
  - Most of the tasks are aperiodic
  - Requirements for system resources can change dramatically for the consecutive task activations, but there are limits known in advance or their statistical distribution is known.
  - **Examples:** multimedia communication, radar signal processing and tracking facilities
- Asynchronous and non-predictable
  - Most of the events are asynchronous
  - Task with high level of complexity
  - **Examples:** real-time control with artificial intelligence, real-time simulation, virtual reality

Job and task description



- ↑ = 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_{ij}) is 7.
- Response time (R_{ij}) is 6.

Terminology – detail

- Task τ_i: A set of jobs executed in order to perform certain function in the system, e.g. airplane stabilization.
- Job J_{ij}: An instance of task.
- Jobs need resources.
  - **Examples of resources:** CPU, network, critical section, shovel
  - Resources that can perform some work are called processors.
- Release time r_{ij}: Time instant when a job is ready to be executed.
- Deadline d_{ij}: Time instant by which the job has to be finished.
- Relative deadline D_i: Difference between deadline and release time.
- Response time R_{ij}: Completion time minus release time.
- Execution (computation) time C_{ij}: Time needed to execute a job if runs alone on a processor.
- Feasible interval of a job: Interval between r_{ij} and d_{ij}.

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?).

Reference model of RT systems

- Each job J_i is characterized by its
  - timing parameters,
  - functional parameters,
  - resource describing parameters and
  - dependencies between individual jobs.
- Each job J_i has its release time r_i, deadline d_i, relative deadline D_i, computation time C_i (often called execution time or worst-case execution time, WCET).
- Occasionally, some parameters are defined as ranges. E.g $r_i \in \langle r_i^-, r_i^+ \rangle$. The size of the interval is called release-time jitter.
- Similarly, execution time can be given as interval $\langle C_i^-, C_i^+ \rangle$.
  - Determination of exact value of C_i might be difficult. Why?

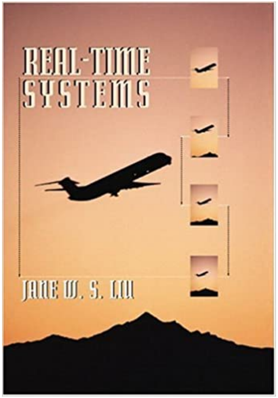
Periodic, sporadic and aperiodic task models

- Periodic task model – deterministic workload model, well suited for many hard real-time applications.
- Periodic task:
  - Each task τ_i has its period T_i. Task τ_i is composed of sequence of jobs.
  - T_i is minimal inter-arrival time between consecutive jobs.
  - Task computation time is the maximum computation time among all jobs of τ_i.
- Sporadic and aperiodic tasks – released at arbitrary times.
  - Sporadic tasks have hard deadlines.
  - Aperiodic tasks have no or soft deadlines.

Liu vs. rest of the world

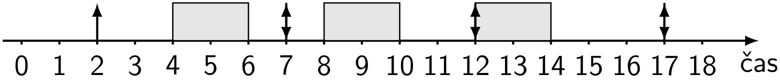
Beware!

- What Liu calls "periodic" the rest of the world calls "sporadic".
- For others period T_i of task τ_i means exact time between activations of two consecutively released jobs.



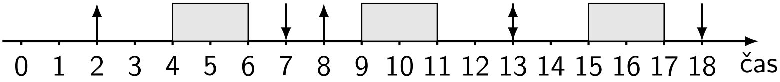
Examples

Periodic task τ_i with $r_i = 2,\ T_i = 5,\ C_i = 2,\ D_i = 5$ can be executed like this (continues until infinity).



Legend: ↑ = job release time , ↓ = deadline.

According to Liu, this task can execute, for example, like this:



The rest of the world calls this sporadic task.

Some definitions for periodic task systems

- Number of tasks is n.
- The jobs of task τ_i are denoted $J_{i,1}$, $J_{i,2}$, ...
- $\Phi_i = r_{i,1}$ (release time of $J_{i,1}$) is called the phase τ_i.
  - Synchronous system: Each task has phase of 0.
  - Asynchronous system: Phases are arbitrary.
  - What is more common?
- Hyperperiod: Least common multiple of $\{T_1, ..., T_n\}$.
- Task utilization: $u_i = \frac{C_i}{T_i}$.
- System utilization: $U = \sum_{i=1,...,n} u_i$

Task/job dependencies

- Data flow and control dependencies between the jobs can constrain the order in which the jobs can be executed.
- Two main types of dependencies:
  - Mutual exclusion (critical sections)
  - Precedence constraints – e.g.: Job J_i can start only after another job J_k finishes.
- Tasks without any dependency on other tasks are called independent.
  - In the initial lectures, we will only consider independent tasks.
  - Software tasks running under a (RT)OS are rarely independent.

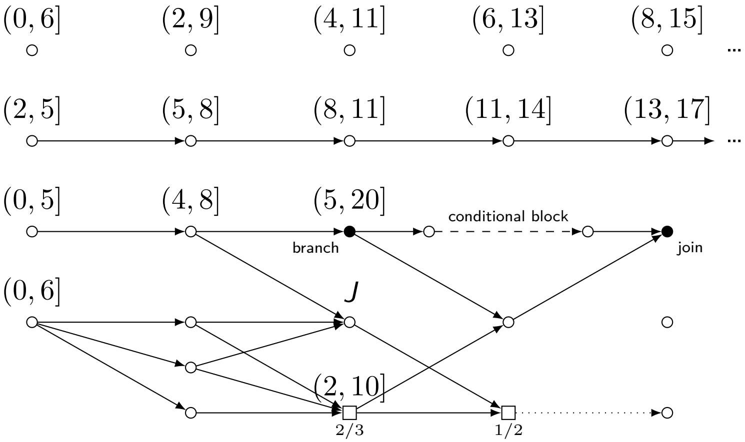
Job dependencies

- Precedence relation on a set of jobs is a relation, that determines precedence constrains among individual jobs.
- Job J_i is a predecessor of another job J_k (and J_k is successor of job J_i), if J_k cannot be started before J_i is finished.
- A job with predecessor is ready to be executed, when current time is greater than its release time and all its predecessors are completed.

Task graph

- Precedence graph – directed graph $G = (J, <)$, where each node represents a job from set J and if job J_i is immediate predecessor of J_k (relation $<$), there is a directed edge from node J_i to node J_k.
  - Data dependencies cannot be captured in the precedence graph.
- Task graph is an extended precedence graph. It can contain other types of dependencies.
  - Type of an edge connecting two nodes and other parameters of the edge is called interconnection parameters of the jobs.
  - Data dependencies are represented explicitly by data-dependency edges. An interconnection parameter can be, for example, the amount of data passed between the jobs.
  - Task graphs are rarely used periodic-task systems.

Task graph – example



- Numbers above a job give its feasible interval.

Other types of dependencies

- Time dependency (distance) is difference of job completion times.
- AND/OR precedence constraints – dependence among immediate job predecessors.
  - AND job – node *J*
  - OR jobs – square nodes marked $2/3$ a $1/2$.
- Conditional branches represent conditional execution of jobs.
  - Branch is a job represented by filled circles.
  - Conditional block – subgraph starting in a *branch* node and ending at next *join* job.
- Pipe relation is dependency among a pair of jobs that are in produce-consumer relation (dotted hrana).

Functional parameters

- Preemptivity of jobs
    - Preemptive
    - Non-preemptive
- Criticality of jobs
- Optional execution
- Laxity type and laxity function

Outline

Terminology

- Processors P_i (active resources) execute machine instructions, move data, read files etc.
  (CPU, communication links, disks, database servers)
- Resources R_i (passive resources) – additional resources needed by jobs to perform their task (memory, mutexes, semaphores). By resources we usually understand "reusable resources".
- Non-reusable resource is, for example, Energy (power-aware scheduling).

Resource parameters

- Processors
  - Speed of a processor
  - Topology of CPU interconnect/network-on-chip
- Preemptivity of resources (CPU, network, ...)
- Memory hierarchy (caches, DRAMs, ...)
- Resource graph
- Wake-up delay from power-saving state
- ...

Outline

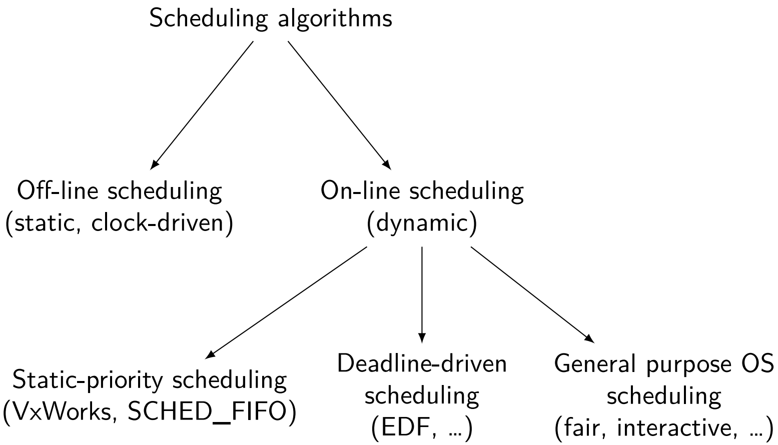
Scheduling algorithms

We are interested in two types of algorithms:

1. Scheduling algorithm, which produces the schedule of jobs (maybe at runtime).
    - In real-time systems, this algorithm is usually simple.
2. Schedulability analysis algorithm, which verifies whether all timing constraints are met.
    - This algorithm is typically more complex.

Classification of scheduling algorithms

(used in real-time systems)



Feasibility and optimality

- A valid schedule is a feasible schedule if every job completes by its deadline (or, in general, meets its timing constraints).
- A set of jobs τ is schedulable according to scheduling algorithm $\mathcal{A}$ if when using the algorithm scheduler always produces a feasible schedule for τ.
- Hard real-time scheduling algorithm is optimal if the algorithm always produces a feasible schedule if the given set of jobs has feasible schedules.
    - Similarly, we can define optimality for a class of schedulers – e.g.. "optimal scheduler for static priorities".

Outline

Model of a real-time system

Comprises of the following parts:

1. Workload model
   - Set of tasks/jobs and their parameters (C_i, D_i, resource dependencies, etc.)
   - Precedence graph or task graph
   - etc.
2. Resource model
   - Description of resources (CPU, memory, network, etc.), their types and relations among them.
   - Often: resource model is just "Uni-processor".
3. Algorithms
   - Fixed-priority scheduler + priority inheritance
   - Off-line scheduler

Real-Time system model – example