SWE 760
Lecture 1:
Introduction to Analysis & Design of Real-Time Embedded Systems

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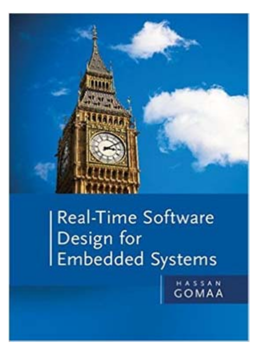
References:

H. Gomaa, Chapters 1, 2, 3 - *Real-Time Software Design for Embedded Systems*, Cambridge University Press, 2016

Software Modeling and Design for Real-Time Embedded Systems

- COMET/RTE method
  - Software Design for RT embedded systems
  - From Use Case Models to Software Architecture
    - Uses UML, SysML and MARTE notations
  - Requirements and Analysis Modeling
    - Use case modeling
    - Static and Dynamic modeling
  - Design modeling
    - Concurrent, distributed, real-time embedded systems
  - H. Gomaa, *Real-Time Software Design for Embedded Systems*, Cambridge University Press, 2016



Software Modeling and Design for Single Systems

- COMET: General software modeling and design method
- Requirements and Analysis Modeling
- Software design modeling
  - Develop software architecture using architectural design patterns
    - Object-Oriented Software Architectures
    - Client/Server Software Architectures
    - Service-Oriented Architectures
    - Component-Based Software Architectures
    - Concurrent and Real-Time Software Architectures
    - Software Product Line Architectures
  - *H. Gomaa, Software Modeling and Design: UML, Use Cases, Patterns, and Software Architectures*, Cambridge University Press, 2011

Software Modeling and Design for Software Product Lines

- Software Product Line (SPL)
  - Family of products / systems (Parnas, Weiss, SEI)
- Software Modeling and Design for SPL
  - Model commonality and variability among members of SPL
  - PLUS method for SPL
    - Extends COMET, other methods for single systems
    - Integrate Feature Modeling with UML
    - Unifying View of Multiple-View Modeling Approach
    - Apply standard UML extension mechanisms
- *H. Gomaa, "Designing Software Product Lines with UML", Addison Wesley, 2005*

Comparison of COMET and COMET/RTE

COMET	COMET/RTE
General design method on software modeling and design	Focused design method on real-time software design
Has one chapter on each kind of software architecture. Real-time software architectures covered in one chapter.	Focus entirely on the design of real-time embedded systems, including real-time design patterns.
Main in-class case study is client/server system: Banking System.	Focus on real-time embedded system case studies.
Does not address issues specific to RT systems	Addresses issues specific to RT systems: - Address systems engineering issues. - Design of hardware/software interface - More details on state machine modeling - Component-based RT software design - Real-Time scheduling and performance analysis - Quality of Service - Dynamic RT software adaptation

Unified Modeling Language (UML)

- A standardized notation for object-oriented development
- A graphical language for describing the products of OO requirements, analysis, and design
- Approved as a standard by Object Management Group (OMG)
- Methodology independent
- Needs to be used with an analysis and design method

MARTE

- Modeling and Analysis of Real-Time Embedded systems
- UML profile
  - Extension of UML for a specific application domain
- MARTE
  - Profile supports concepts for real-time embedded systems

SysML

- Systems Modeling Language
  - Standardized notation for modeling system requirements
  - Approved as a standard by Object Management Group (OMG)
  - Methodology independent
- General-purpose graphical modeling language
  - specifying, analyzing, designing, and verifying complex systems
    - Hardware
    - software
    - information
    - personnel
    - Procedures

Model Driven Architecture

- Promoted by Object Management Group (OMG)
- Model Driven Architecture
  - Develop UML models of software architecture before implementation
- Platform Independent Model (PIM)
  - Precise model of software architecture before commitment to specific platform
- Platform Specific Model (PSM)
  - Map PIM UML model to a specific hardware/middleware platform
    - E.g., .NET, J2EE, Web Services, Real-Time platforms
- Real-time systems need to be mapped to PSM for performance analysis

Real-Time Systems

- Hard real-time systems
  - Time-critical deadlines
  - System failure could be catastrophic
  - Safety critical systems
- Soft real-time systems
  - Interactive systems
  - Missing deadlines is undesirable but not catastrophic
- Real-Time Embedded System
  - Component of larger hardware/software system
  - Has mechanical or electrical parts
    - E.g., aircraft, automobile, train

Real-Time Embedded Systems and Applications

- Real-Time Embedded System
  - Real -Time Embedded Application
    + Real-Time Operating System
    + Computer Hardware

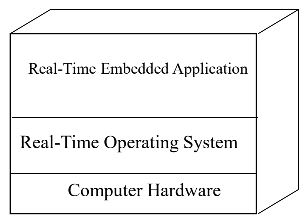


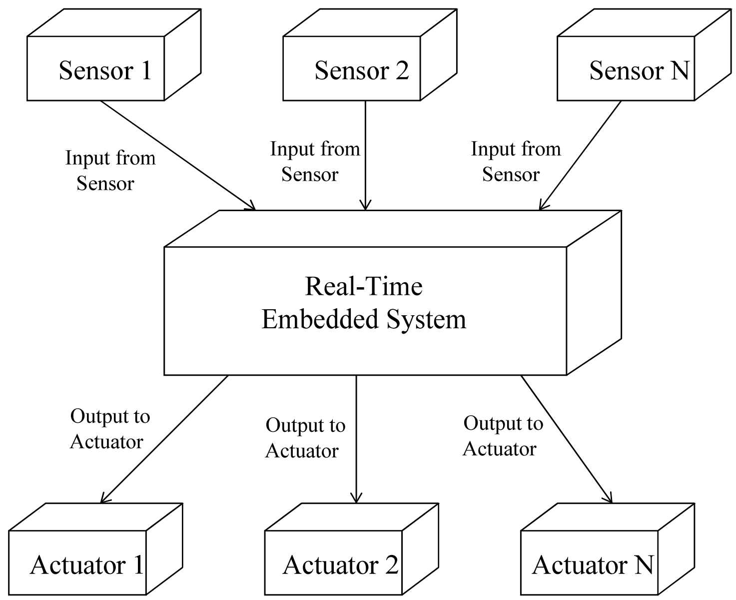
Figure 1.2: Layered architecture of real-time embedded system

Characteristics of Real-Time Embedded Systems

- Interaction with external environment
  – Input from sensors
  – Output to actuators
- Timing constraints
  – Must process input event within given time
- Real-time control
  – Make control decision based on input data
  – Without human intervention
- Reactive systems
  – System responds to external events
  – Response is often state dependent
- Concurrency
  – Many events happening in parallel

Figure 1.1 Real-Time System

(UML Deployment Diagram)



Measuring Time

- **Event**
  - Occurs at an instant of time
- **Duration**
  - Interval of time between
    - starting event
    - terminating event
- **Period**
  - Measurement of recurring intervals of same duration
- **Execution time**
  - CPU time taken to execute a given task
- **Elapsed time**
  - Total time to execute a task from start to finish

Measuring Time

- **Elapsed time** = **Execution time** + **Blocked time**
- **Blocked time**
  - Waiting time when the task is not using the CPU
    - Waiting for I/O operations to complete
    - Waiting for messages or responses to arrive
    - Waiting to be assigned the CPU
    - Waiting for entry into critical sections
- **Physical time** (or real-world time)
  - Total time for a real-time command to be completed
  - E.g., to stop a train
  - **Physical time** = **Elapsed time** + time to physically stop train

Real-Time Control

- Consider as a process control problem
- Speed control algorithm of automated train
  - Set point: target cruising speed
  - Controlled variable: current speed of train
- Speed control algorithm
  - Compares set point with controlled variable
  - Increasing or decreases the current speed of train
  - Goal: current speed = cruising speed +/- delta
- Adjustments to speed converted to voltage applied to electric motor
- Speed sensor measures current speed of train

Real-Time Control

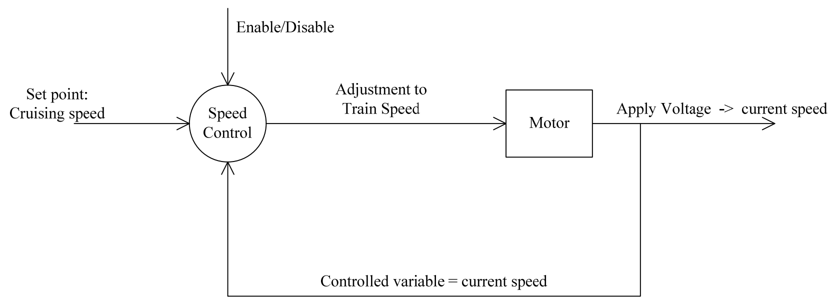


Figure 1.3 Speed control algorithm for software controlled train

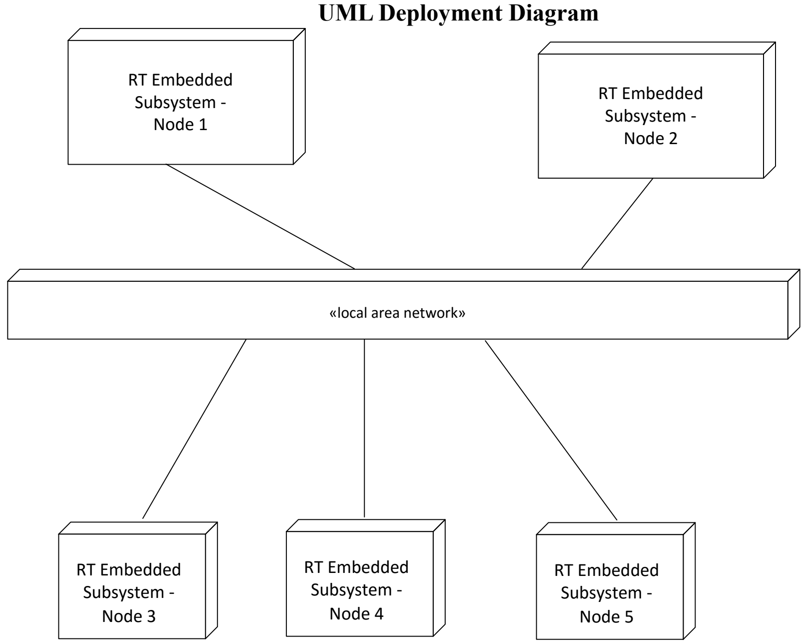
Note: This figure does not conform to the UML notation

Characteristics of Distributed RT Applications

- Distributed processing environment
  - Multiple computers communicating over network
- Typical applications
  - Distributed real-time data collection
  - Distributed real-time control
  - RT Client / server applications

Figure 1.4 Example of Distributed Real-Time Embedded System

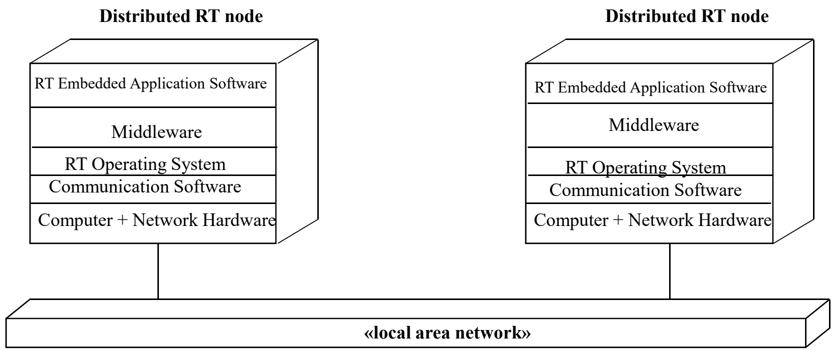
UML Deployment Diagram



Distributed RT Embedded Systems

- Distributed RT Embedded System
  - Distributed RT Embedded Application
    + Middleware
    + RT Operating System
    + Communication Software
    + Computer & Network Hardware
  - Communication Software = Network protocol software
  - Middleware
    - Software layer provides uniform platform
  – Distributed OS often integrates middleware with OS

Figure 1.5: Layered Architecture for Distributed RT Embedded System



UML Deployment Diagram

Advantages of Distributed RT Processing

- **Distributed Control**
  – Control distributed among multiple nodes
  – Hierarchical control
  – Peer-to-peer control
- **More localized control and management**
  – Design distributed subsystem to be autonomous
  – Subsystem on node
    - Relatively independent of other subsystems on other nodes
- **More flexible configuration**
  – A given application can be configured in different ways

Advantages of Distributed RT Processing

- **Improved availability**
  - Operation is feasible in a reduced configuration
  - There is no single point of failure
- **Incremental system expansion**
  - System can be expanded by adding more nodes
- **Load balancing**
  - Overall system load can be shared among several nodes

Internet of Things (IoT)

- Interconnect physical "things" to the Internet
- Connect remote sensors and actuators to the Internet
- Remote access to sensor data
  - RFID technology
  - Electronic RFID tag is attached to a physical product
  - Product + RFID
    - Smart object uniquely identified over Internet
- IoT
  - Integrate real-time embedded systems with the Internet

Cyber-Physical Systems

- Smart networked systems with embedded sensors, processors and actuators
- Designed to sense and interact with the physical world
- Support real-time, guaranteed performance in safety-critical applications
- Joint behavior of "cyber" and "physical" elements
- Embedded cyber system
  - Monitors and controls physical processes
- E.g., automated train
  - Cyber subsystem: Real-time automated control
  - Physical subsystems: electric motor, braking system, transmission, smart sensors and actuators

Software Design Concepts for Real-Time Systems

- Concurrent tasks
  - For structuring system into components that execute in parallel
  - Key concept for designing concurrent, real-time, and distributed systems
- Finite state machines
  - Key concept for defining control aspects of real-time systems
- Information hiding
  - For structuring system into modifiable components
  - Key concept for object-oriented design

Sequential & Concurrent Problems

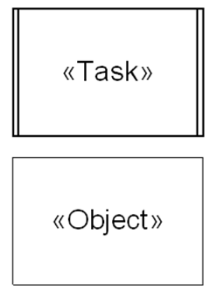
- Sequential problems
  - Activities happen in strict sequence
    - E.g., compiler, payroll
  - Sequential solution = program
- Concurrent problems
  - Many activities happen in parallel
    - E.g., multi-user interactive system, air traffic control system
  - Sequential solution to concurrent problem increases design complexity

Concurrency

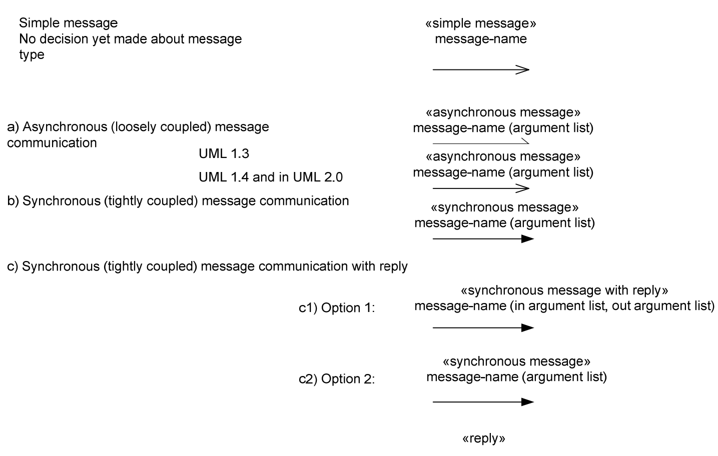
- Characteristics of concurrent task
  - A.k.a. (lightweight) process, thread
    - Active object, concurrent object
  - One sequential thread of execution
  - Represents execution of
    - Sequential program
    - Sequential part of concurrent program
  - Concurrent system
    - Many tasks execute in parallel
    - Tasks need to interact with each other

Active and Passive Objects

- Objects may be **active** or **passive**
- **Active object**
  - **Concurrent Task**
  - Has thread of control
- **Passive object**
  - a.ka. **Information Hiding Object**
  - Has no thread of control
  - Operations of passive object are executed by task
  - Operations execute in task's thread of control
    - Directly or indirectly
- Software Design terminology
  - **Task** refers to active object
  - **Object** refers to passive object



UML notation for messages



Examples of Concurrent Processing

Figure 3.7 Asynchronous message communication

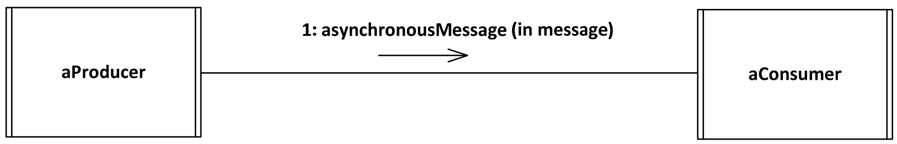
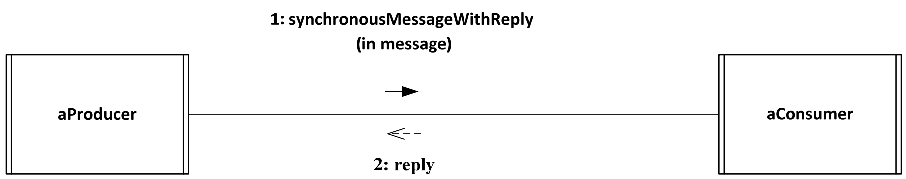
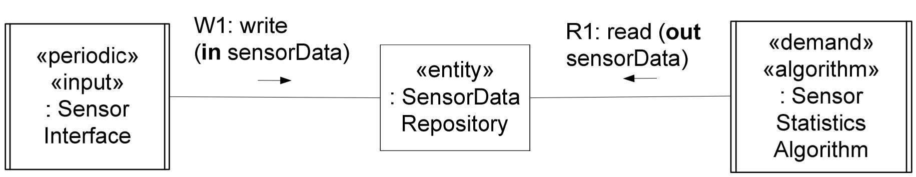


Figure 3.8 Synchronous message communication with reply



Task Communication via Information Hiding Object

- Passive object
  - Encapsulates data
  - Hides contents of data structure
  - Data accessed indirectly via operations
- Passive object accessed by two or more tasks
  - Operations must synchronize access to data
  - Use semaphore or monitor object



Interaction Between Concurrent Tasks

- Mutual exclusion
  - Two or more tasks need to access shared data
  - Access must be mutually exclusive
- Binary semaphore
  - Boolean variable that is only accessed by means of two atomic (indivisible) operations
  - **acquire (semaphore)**
    - if the resource is available, then get the resource
    - if resource is unavailable, wait for resource to become available
  - **release (semaphore)**
    - signals that resource is now available
    - if another task is waiting for the resource, it will now acquire the resource

Run-Time Support for Concurrent Tasks

- Operating System Services
  - Multi-tasking Kernel
    - Task creation and deletion
    - Priority pre-emption task scheduling
    - Mutual exclusion using semaphores
    - Inter-task synchronization using events
    - Inter-task communication using messages
- Language Support for Concurrent Tasks, e.g., Java
  - Concurrent tasking constructs
  - Task creation and deletion
  - Support for inter-task communication and synchronization

Task Scheduling Algorithms

- Round-robin scheduling
  - Tasks have same priority
  - FIFO queuing and CPU allocation of tasks on Ready List
  - Task executes for time slice or blocks
  - NOT satisfactory for Real-Time System
- Priority pre-emption task scheduling
  - Each task is assigned a priority
  - Task(s) with highest priority assigned to CPU
  - Task executes until
    - it blocks or
    - is pre-empted by higher priority task

State Machine
Execution Cycle of Concurrent Task

- Ready State
  - Task on Ready List
- Executing State
  - Task is removed from Ready List and assigned CPU
- Blocking States – Task blocks and is
  - Waiting for I/O
  - Waiting for Event
  - Waiting for Message
  - Waiting to Enter Critical Section

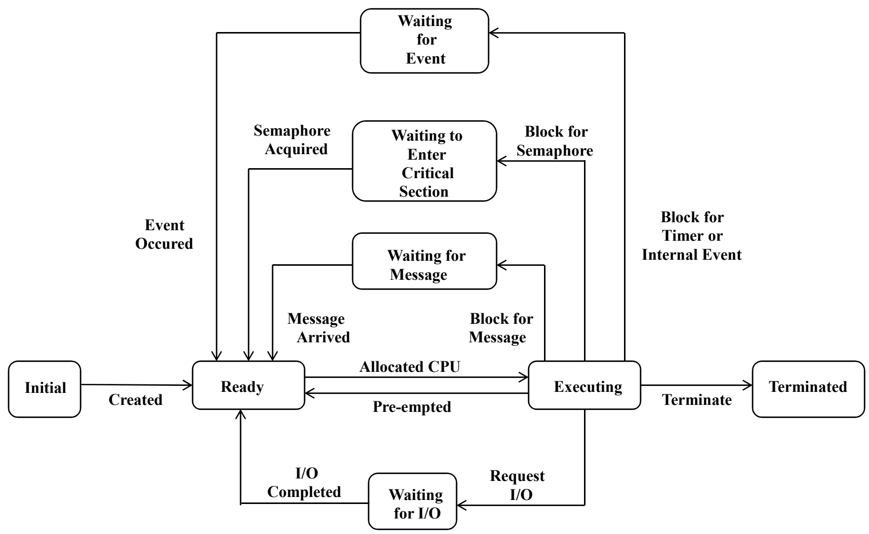


Figure 3.9 State machine for concurrent task

Finite State Machines

- Many information and real-time systems are state dependent
  - Action depends not only on input event
  - Also depends on state of system
- Finite State Machine
  - Finite number of states
  - Only in one state at a time
- State
  - A recognizable situation
  - Exists over an interval of time
- Event
  - A discrete signal that happens at a point in time
  - Causes change of state

Information Hiding

Each object hides design decision
- E.g., data structure
  - interface to I/O device

Information hiding object
- Hides (encapsulates) information
- Accessed by operations

Basis for Object-Oriented Design

Advantage
- Objects are more self-contained
- Results in more modifiable -> maintainable system

Example of Information Hiding

- Example of Analog Sensor Repository class
- Information hiding solution
  - Hide internal data structure and internal linkage
  - Specify operations on data structure
  - Access to class only via operations
    - readAnalogSensor
    - updateAnalogSensor

Example of Information Hiding

«data abstraction»
AnalogSensorRepository

+ readAnalogSensor(**in** sensorID, **out** sensorValue, **out** upperLimit, **out** lowerLimit, **out** alarmCondition)
+ updateAnalogSensor (sensorID, sensorValue)

Goals of Real-Time Design Method

- Capability of structuring system into concurrent components
  - Concurrent task structuring
- Development of maintainable and reusable software
  - Information hiding
  - Inheritance
- Definition of system control and sequencing
  - Finite state machines
  - Event sequence scenarios
- Component-based software architecture
  - Concurrent OO components and connectors
- Capability to analyze performance of design
  - Real-Time scheduling

Requirements for Real-Time Software Design Method

- **Structural modeling**
  - Model problem domain, system (hardware and software) boundary, software system boundary
- **Dynamic (behavioral) modeling**
  - Model interaction sequences between system and software artifacts
- **State machines**
  - React to external events given current state of system
- **Concurrency**
  - Model activities that execute in parallel with each other

Requirements for Real-Time Software Design Method

- **Component-based software architecture**
  - concurrent object-oriented components and connectors,
  - components deployed to different nodes in distributed environment
- **Performance analysis of real-time designs**
  - Analyze the performance of the real-time system before implementation
  - Determine whether the system will meet its performance goals.

Characteristics of RT Embedded Systems

Reactive systems
- Control decisions are often state dependent
  - *Finite state machines*

Concurrent inputs from many sources
- *Concurrent Processing*

Real-time requirements
- Need to analyze performance of design
  - *Real-Time scheduling*

Develop maintainable and reusable software
- Need to integrate RT technology with modern software engineering concepts and methods
  - *RT Software Engineering*

Figure 4.1 COMET/RTE life cycle model