Real-time Software Design

Objectives

- To explain the concept of a real-time system and why these systems are usually implemented as concurrent processes
- To describe a design process for real-time systems
- To explain the role of a real-time operating system
- To introduce generic process architectures for monitoring and control and data acquisition systems

Topics covered

- System design
- Real-time operating systems
- Monitoring and control systems
- Data acquisition systems

Real-time systems

- Systems which monitor and control their environment.
- Inevitably associated with hardware devices
  - Sensors: Collect data from the system environment;
  - Actuators: Change (in some way) the system's environment;
- Time is critical. Real-time systems MUST respond within specified times.

Definition

- A real-time system is a software system where the correct functioning of the system depends on the results produced by the system and the time at which these results are produced.
- A soft real-time system is a system whose operation is degraded if results are not produced according to the specified timing requirements.
- A hard real-time system is a system whose operation is incorrect if results are not produced according to the timing specification.

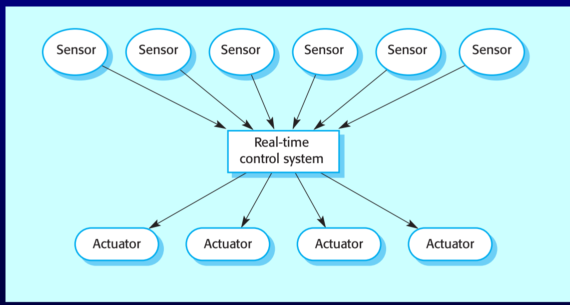
Stimulus/Response Systems

- Given a stimulus, the system must produce a response within a specified time.
- Periodic stimuli. Stimuli which occur at predictable time intervals
  - For example, a temperature sensor may be polled 10 times per second.
- Aperiodic stimuli. Stimuli which occur at unpredictable times
  - For example, a system power failure may trigger an interrupt which must be processed by the system.

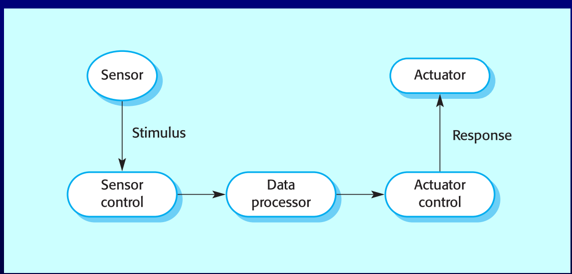
Architectural considerations

- Because of the need to respond to timing demands made by different stimuli/responses, the system architecture must allow for fast switching between stimulus handlers.
- Timing demands of different stimuli are different so a simple sequential loop is not usually adequate.
- Real-time systems are therefore usually designed as cooperating processes with a real-time executive controlling these processes.

A real-time system model



Sensor/actuator processes



System elements

- Sensor control processes
  - Collect information from sensors. May buffer information collected in response to a sensor stimulus.
- Data processor
  - Carries out processing of collected information and computes the system response.
- Actuator control processes
  - Generates control signals for the actuators.

Real-time programming

Real-time programming

- Hard-real time systems may have to programmed in assembly language to ensure that deadlines are met.
- Languages such as C allow efficient programs to be written but do not have constructs to support concurrency or shared resource management.

Java as a real-time language

- Java supports lightweight concurrency (threads and synchronized methods) and can be used for some soft real-time systems.
- Java 2.0 is not suitable for hard RT programming but real-time versions of Java are now available that address problems such as
  - Not possible to specify thread execution time;
  - Different timing in different virtual machines;
  - Uncontrollable garbage collection;
  - Not possible to discover queue sizes for shared resources;
  - Not possible to access system hardware;
  - Not possible to do space or timing analysis.

System design

- Design both the hardware and the software associated with system. Partition functions to either hardware or software.
- Design decisions should be made on the basis on non-functional system requirements.
- Hardware delivers better performance but potentially longer development and less scope for change.

R-T systems design process

- Identify the stimuli to be processed and the required responses to these stimuli.
- For each stimulus and response, identify the timing constraints.
- Aggregate the stimulus and response processing into concurrent processes. A process may be associated with each class of stimulus and response.

R-T systems design process

- Design algorithms to process each class of stimulus and response. These must meet the given timing requirements.
- Design a scheduling system which will ensure that processes are started in time to meet their deadlines.
- Integrate using a real-time operating system.

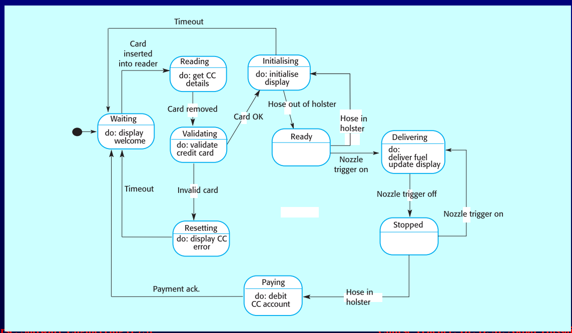
Timing constraints

- May require extensive simulation and experiment to ensure that these are met by the system.
- May mean that certain design strategies such as object-oriented design cannot be used because of the additional overhead involved.
- May mean that low-level programming language features have to be used for performance reasons.

Real-time system modelling

- The effect of a stimulus in a real-time system may trigger a transition from one state to another.
- Finite state machines can be used for modelling real-time systems.
- However, FSM models lack structure. Even simple systems can have a complex model.
- The UML includes notations for defining state machine models
- See Chapter 8 for further examples of state machine models.

Petrol pump state model



Real-time operating systems

- Real-time operating systems are specialised operating systems which manage the processes in the RTS.
- Responsible for process management and resource (processor and memory) allocation.
- May be based on a standard kernel which is used unchanged or modified for a particular application.
- Do not normally include facilities such as file management.

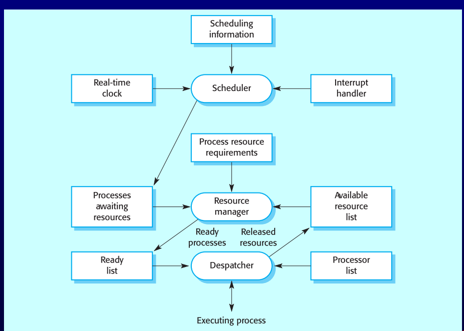
Operating system components

- Real-time clock
  - Provides information for process scheduling.
- Interrupt handler
  - Manages aperiodic requests for service.
- Scheduler
  - Chooses the next process to be run.
- Resource manager
  - Allocates memory and processor resources.
- Dispatcher
  - Starts process execution.

Non-stop system components

- Configuration manager
  - Responsible for the dynamic reconfiguration of the system software and hardware. Hardware modules may be replaced and software upgraded without stopping the systems.
- Fault manager
  - Responsible for detecting software and hardware faults and taking appropriate actions (e.g. switching to backup disks) to ensure that the system continues in operation.

Real-time OS components



Process priority

- The processing of some types of stimuli must sometimes take priority.
- Interrupt level priority. Highest priority which is allocated to processes requiring a very fast response.
- Clock level priority. Allocated to periodic processes.
- Within these, further levels of priority may be assigned.

Interrupt servicing

- Control is transferred automatically to a pre-determined memory location.
- This location contains an instruction to jump to an interrupt service routine.
- Further interrupts are disabled, the interrupt serviced and control returned to the interrupted process.
- Interrupt service routines MUST be short, simple and fast.

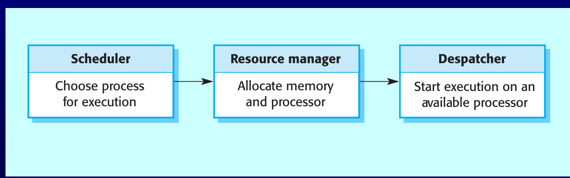
Periodic process servicing

- In most real-time systems, there will be several classes of periodic process, each with different periods (the time between executions), execution times and deadlines (the time by which processing must be completed).
- The real-time clock ticks periodically and each tick causes an interrupt which schedules the process manager for periodic processes.
- The process manager selects a process which is ready for execution.

Process management

- Concerned with managing the set of concurrent processes.
- Periodic processes are executed at pre-specified time intervals.
- The RTOS uses the real-time clock to determine when to execute a process taking into account:
  - Process period - time between executions.
  - Process deadline - the time by which processing must be complete.

RTE process management



Process switching

- The scheduler chooses the next process to be executed by the processor. This depends on a scheduling strategy which may take the process priority into account.
- The resource manager allocates memory and a processor for the process to be executed.
- The dispatcher takes the process from ready list, loads it onto a processor and starts execution.

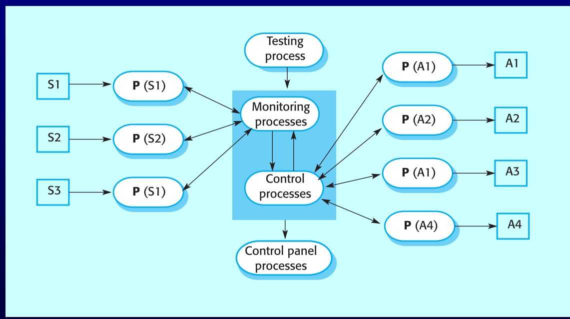
Scheduling strategies

- Non pre-emptive scheduling
  - Once a process has been scheduled for execution, it runs to completion or until it is blocked for some reason (e.g. waiting for I/O).
- Pre-emptive scheduling
  - The execution of an executing processes may be stopped if a higher priority process requires service.
- Scheduling algorithms
  - Round-robin;
  - Rate monotonic;
  - Shortest deadline first.

Monitoring and control systems

- Important class of real-time systems.
- Continuously check sensors and take actions depending on sensor values.
- Monitoring systems examine sensors and report their results.
- Control systems take sensor values and control hardware actuators.

Generic architecture



Burglar alarm system

- A system is required to monitor sensors on doors and windows to detect the presence of intruders in a building.
- When a sensor indicates a break-in, the system switches on lights around the area and calls police automatically.
- The system should include provision for operation without a mains power supply.

Burglar alarm system

- Sensors
  - Movement detectors, window sensors, door sensors;
  - 50 window sensors, 30 door sensors and 200 movement detectors;
  - Voltage drop sensor.
- Actions
  - When an intruder is detected, police are called automatically;
  - Lights are switched on in rooms with active sensors;
  - An audible alarm is switched on;
  - The system switches automatically to backup power when a voltage drop is detected.

The R-T system design process

- Identify stimuli and associated responses.
- Define the timing constraints associated with each stimulus and response.
- Allocate system functions to concurrent processes.
- Design algorithms for stimulus processing and response generation.
- Design a scheduling system which ensures that processes will always be scheduled to meet their deadlines.

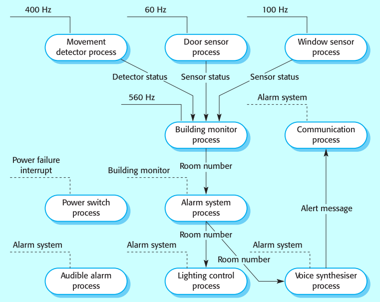
Stimuli to be processed

- Power failure
  - Generated aperiodically by a circuit monitor. When received, the system must switch to backup power within 50 ms.
- Intruder alarm
  - Stimulus generated by system sensors. Response is to call the police, switch on building lights and the audible alarm.

Timing requirements

Stimulus/Response	Timing requirements
Power fail interrupt	The switch to backup power must be completed within a deadline of 50 ms.
Door alarm	Each door alarm should be polled twice per second.
Window alarm	Each window alarm should be polled twice per second.
Movement detector	Each movement detector should be polled twice per second.
Audible alarm	The audible alarm should be switched on within 1/2 second of an alarm being raised by a sensor.
Lights switch	The lights should be switched on within 1/2 second of an alarm being raised by a sensor.
Communications	The call to the police should be started within 2 seconds of an alarm being raised by a sensor.
Voice synthesiser	A synthesised message should be available within 4 seconds of an alarm being raised by a sensor.

Burglar alarm system processes



Building_monitor process 1

```
class BuildingMonitor extends Thread {

        BuildingSensor win, door, move ;

        Siren       siren = new Siren () ;
        Lights      lights = new Lights () ;
        Synthesizer synthesizer = new Synthesizer () ;
        DoorSensors doors = new DoorSensors (30) ;
        WindowSensors       windows = new WindowSensors (50) ;
        MovementSensors movements = new MovementSensors (200) ;
        PowerMonitor pm = new PowerMonitor () ;

        BuildingMonitor()
        {
                // initialise all the sensors and start the processes
                siren.start () ; lights.start () ;
                synthesizer.start () ; windows.start () ;
                doors.start () ; movements.start () ; pm.start () ;
        }
```


Building monitor process 2

```
public void run ()
    {
        int room = 0 ;
        while (true)
        {
            // poll the movement sensors at least twice per second (400 Hz)
            move = movements.getVal () ;
            // poll the window sensors at least twice/second (100 Hz)
            win = windows.getVal () ;
            // poll the door sensors at least twice per second (60 Hz)
            door = doors.getVal () ;
            if (move.sensorVal == 1 | door.sensorVal == 1 | win.sensorVal == 1)
                {
                    // a sensor has indicated an intruder
                    if (move.sensorVal == 1)    room = move.room ;
                    if (door.sensorVal == 1)    room = door.room ;
                    if (win.sensorVal == 1 )        room = win.room ;

                    lights.on (room) ; siren.on () ; synthesizer.on (room) ;
                    break ;
                }
        }
```


Building_monitor process 3

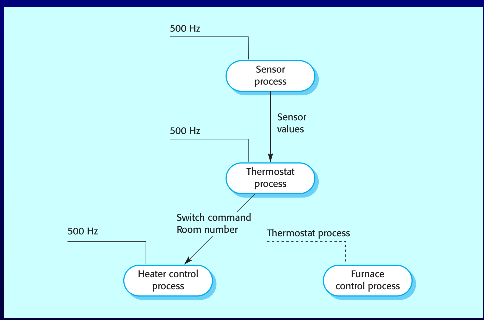
```
        lights.shutdown () ; siren.shutdown () ; synthesizer.shutdown () ;
        windows.shutdown () ; doors.shutdown () ; movements.shutdown () ;

    } // run
} //BuildingMonitor
```


Control systems

- A burglar alarm system is primarily a monitoring system. It collects data from sensors but no real-time actuator control.
- Control systems are similar but, in response to sensor values, the system sends control signals to actuators.
- An example of a monitoring and control system is a system that monitors temperature and switches heaters on and off.

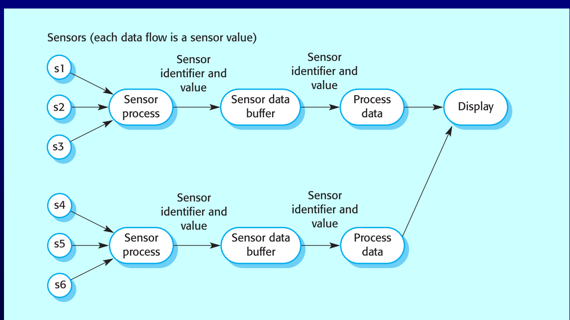
A temperature control system



Data acquisition systems

- Collect data from sensors for subsequent processing and analysis.
- Data collection processes and processing processes may have different periods and deadlines.
- Data collection may be faster than processing e.g. collecting information about an explosion.
- Circular or ring buffers are a mechanism for smoothing speed differences.

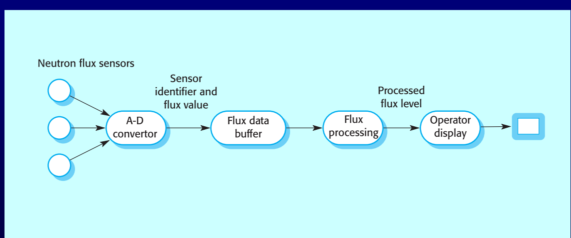
Data acquisition architecture



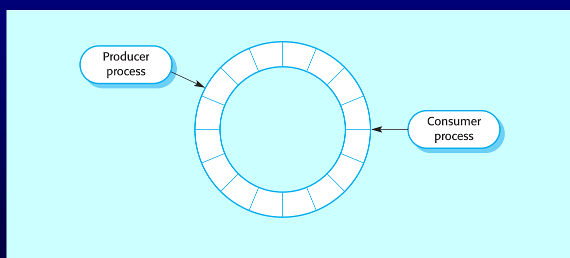
Reactor data collection

- A system collects data from a set of sensors monitoring the neutron flux from a nuclear reactor.
- Flux data is placed in a ring buffer for later processing.
- The ring buffer is itself implemented as a concurrent process so that the collection and processing processes may be synchronized.

Reactor flux monitoring



A ring buffer



Mutual exclusion

- Producer processes collect data and add it to the buffer. Consumer processes take data from the buffer and make elements available.
- Producer and consumer processes must be mutually excluded from accessing the same element.
- The buffer must stop producer processes adding information to a full buffer and consumer processes trying to take information from an empty buffer.

Ring buffer implementation 1

```
class CircularBuffer
{
        int bufsize ;
        SensorRecord [] store ;
        int numberOfEntries = 0 ;
        int front = 0, back = 0 ;

        CircularBuffer (int n) {
                bufsize = n ;
                store = new SensorRecord [bufsize] ;
        } // CircularBuffer
```


Ring buffer implementation 2

```
        synchronized void put (SensorRecord rec )
                throws InterruptedException
        {
                if ( numberOfEntries == bufsize)
                        wait () ;
                store [back] = new SensorRecord (rec.sensorId, rec
                back = back + 1 ;
                if (back == bufsize)
                        back = 0 ;
                numberOfEntries = numberOfEntries + 1 ;
                notify () ;
        } // put
```


Ring buffer implementation 3

```
synchronized SensorRecord get () throws InterruptedException
        {
                SensorRecord result = new SensorRecord (-1, -1) ;
                if (numberOfEntries == 0)
                        wait () ;
                result = store [front] ;
                front = front + 1 ;
                if (front == bufsize)
                        front = 0 ;
                numberOfEntries = numberOfEntries - 1 ;
                notify () ;
                return result ;
        } // get
} // CircularBuffer
```


Key points

- Real-time system correctness depends not just on what the system does but also on how fast it reacts.
- A general RT system model involves associating processes with sensors and actuators.
- Real-time systems architectures are usually designed as a number of concurrent processes.

Key points

- Real-time operating systems are responsible for
  process and resource management.
- Monitoring and control systems poll sensors and send control signal to actuators.
- Data acquisition systems are usually organised according to a producer consumer model.