EE687

Real-Time Control

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Chapter 1. Typical Real-Time Applications

- **Real-time systems** are required
  to complete their works and deliver services
  on a **timely** basis.
  - Ex) digital control,
    command and control (airplane, car),
    signal processing, and telecommunication systems.
  - Malfunctions can have serious consequences

- Scope
  - How to work and deliver valuable services *on time*.
  - Techniques for *validating* real-time systems.

1.1 Digital Control

1.1.1. Sampled Data Systems

- Digital controllers as embedded computer systems
  - Sensor, controller, actuator, and timer.
  - Replacing analog controllers with *sampled-data digital controllers*. ->
  - Analog to/from digital conversion required to interface to analog world.

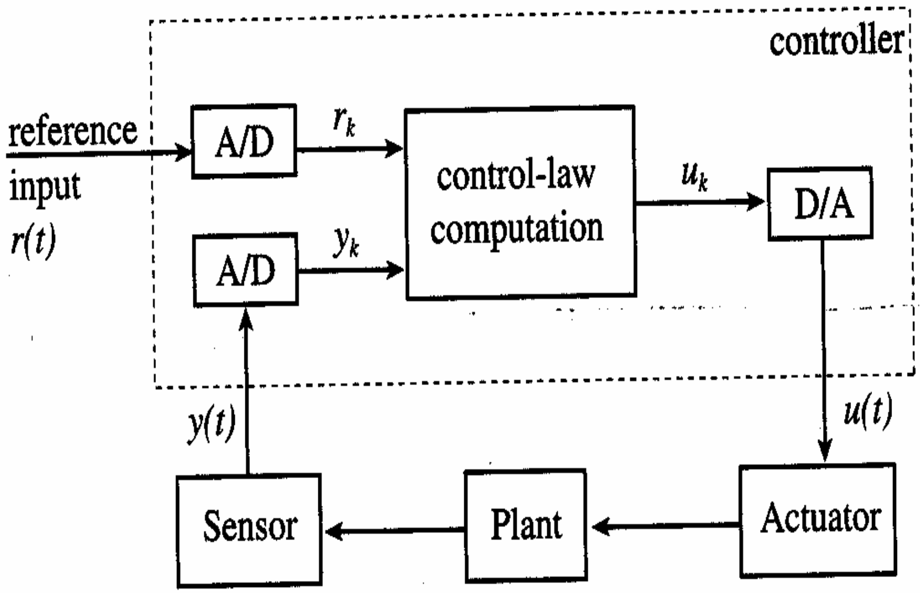


FIGURE 1-1 A digital controller.

A simple example of sampled data systems

- An analog single-input single-output PID (Proportional, Integral, and Derivative) controller.
  - Reference input r(t)
  - Measured plant output y(t)
  - Error y(t) = r(t) – y(t)
  - Control signal ->

$$u(t) = K_P e(t) + K_I \int e(\tau) d\tau + K_D \frac{d}{dt} e(t)$$

- Discrete-time control ->

$$u_k = u_{k-1} + \alpha\, e_k + \beta\, e_{k-1} + \gamma\, e_{k-2}$$

- Sampled-data controller Implementation
  - Set timer to interrupt periodically with period T
  - At each timer interrupt, do
    - Do A/D conversion to get y.
    - Compute control output u.
    - Output u with D/A conversion.
  - Wait for the next sampling time.

Selection of Sampling Period

- **Sampling period T**: time interval between two consecutive samplings of y(t) (and r(t)).
  - Key design choice.
  - Compromise on control performance and computing load.
- Disk drive controller example:

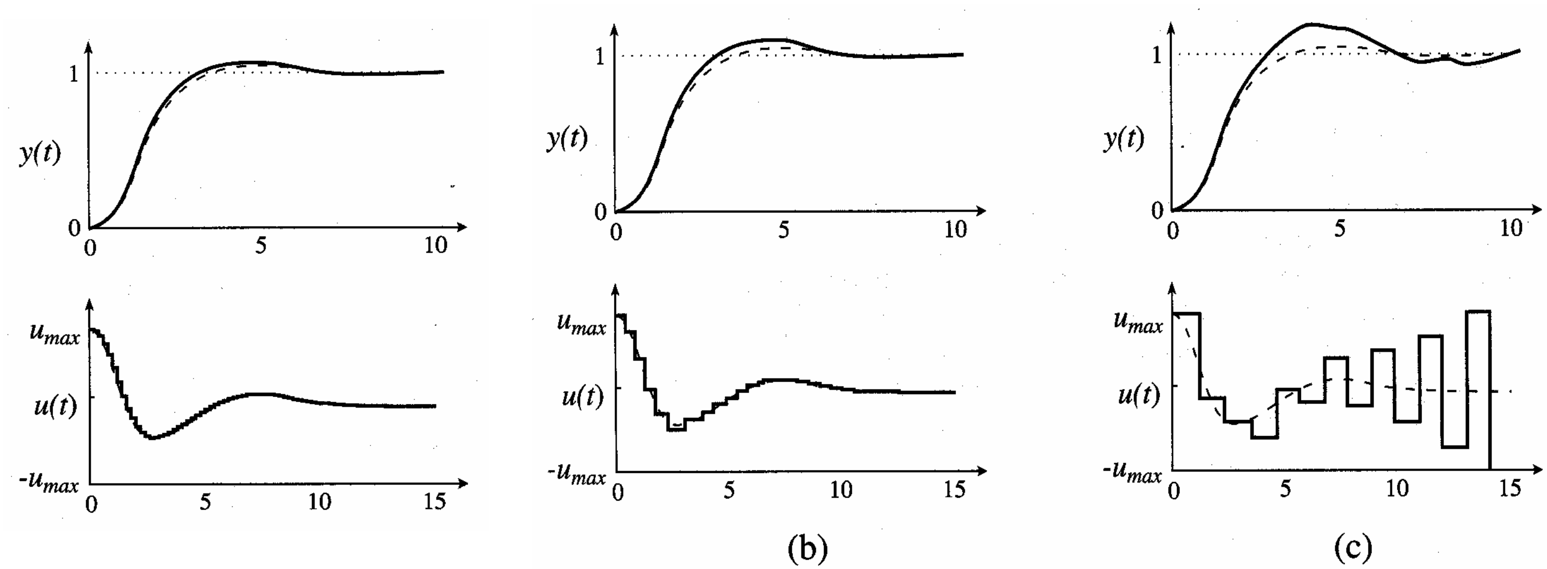


FIGURE 1–2 Effect of sampling period.

Selection of Sampling Period (II)

- Faster plant: smaller rise time R, shorter sampling period T.

- Rule of thumb for selecting T
  - (Rise time r)/(sampling period T) in the range from 10 to 20.
    - 10 to 20 sampling periods within the rise time.

- Lower limit on w
  - Nyquist sampling theorem
    - Sampling rate 2w or higher for systems with bandwidth w.
  - Bandwidth of the overall system ~1/2R Hz.
    - Sampling rate: 20 to 40 times the system bandwidth w.

Multirate Systems

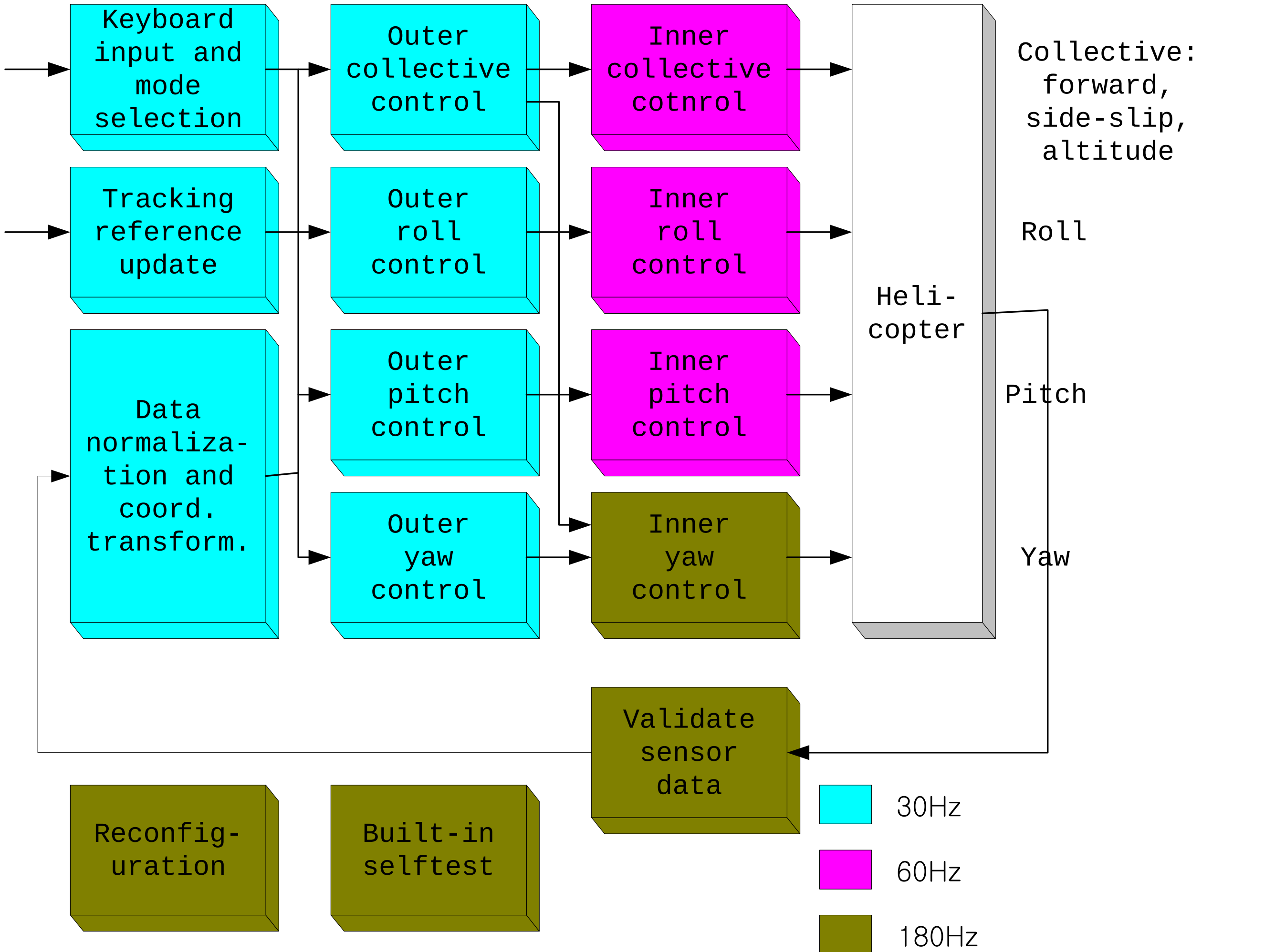
- MIMO (Multiple input multiple output) system
  - Multiple state variables have different dynamics
    - Ex) Engine rotation speed vs. temperature.
  - Uniform smallest sampling period: Waste of processing time.

  - Different sampling periods are desirable.
    - **Harmonic periods**: Each longer sampling period is an integer multiple of every shorter period.
      - Good processor utilization.

  - *Successive loop closure method* (for design and analysis)
    - Assume all controllers are independent
    - Select the fastest controller's T and design the digital controller
    - Convert the controller back to analog form as a plant
    - Integrate into the overall system, and design the next faster controller.

An Example of Software Control Structures

- Flight controller for helicopter



1.1.2 More Complex Control-Law Computations

- Assumptions vs. practices
  - Accurate estimates of state variables: Noise and disturbances are added.
  - Sensor data for state: Partial states are available only.
  - All plant parameters are known: Not known. Estimation req’d.

- Practical digital controller implementation
  - Set timer to interrupt periodically with period T.
  - At each timer interrupt, do
    - Sample and digitize to get plant output y.
    - Compute control output u (using state x).*
    - Output u with D/A conversion.
    - Estimate and update plant parameters p.*
    - Compute and update state variable x.*
  - Wait for the next sampling time.

Kalman Filter

- Very general optimal state estimator (smoothing, filtering, and prediction)
- System with system/measurement noise

$$x_{k+1} = G_k x_k + H_k u_k + w_k$$

$$y_k = C_k x_k + \varepsilon_k$$

- Error covariance

$$E[w_j w_k^*] = Q_k \delta_{jk}$$

$$E[\varepsilon_j \varepsilon_k^*] = R_k \delta_{jk}$$

- Prediction-type Kalman filter

$$\tilde{x}_{k+1} = G_k \tilde{x}_k + H_k u_k + K_k [y_k - C_k \tilde{x}_k]$$

$$K_k = G_k P_k C_k^* [R_k + C_k P_k C_k^*]^{-1}, \quad P_k = E[e_k e_k^*]$$

- With Riccati equation

$$P_{k+1} = Q_k + G_k P_k G_k^* - G_k P_k C_k^* [R_k + C_k P_k C_k^*]^{-1} C_k P_k G_k^*, \quad P_0 = E[e_0 e_0^*]$$

1.2 High-Level Controls
1.2.1 Examples of Control Hierarchy

- **Control hierarchy**
  - Controllers in a complex monitor and control system are typically organized *hierarchically*.

- Patient care system
  - Low level controller: Monitor and control patient's blood pressure, respiration, glucose, etc.
    - Simple, deterministic
    - Period: ms to s.
  - High level controller (expert system): interact with operator.
    - Far more complex and variable.
    - Period: m to h.

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Hierarchy of air traffic/flight control

- Air-Traffic Control (ATC) system
  - Highest level
  - Assign each aircraft an arrival time at each metering fix
- On-board flight management system
  - Time-referenced flight path
- Flight controller
  - Cruise speed, turn radius, descend/ascend rates

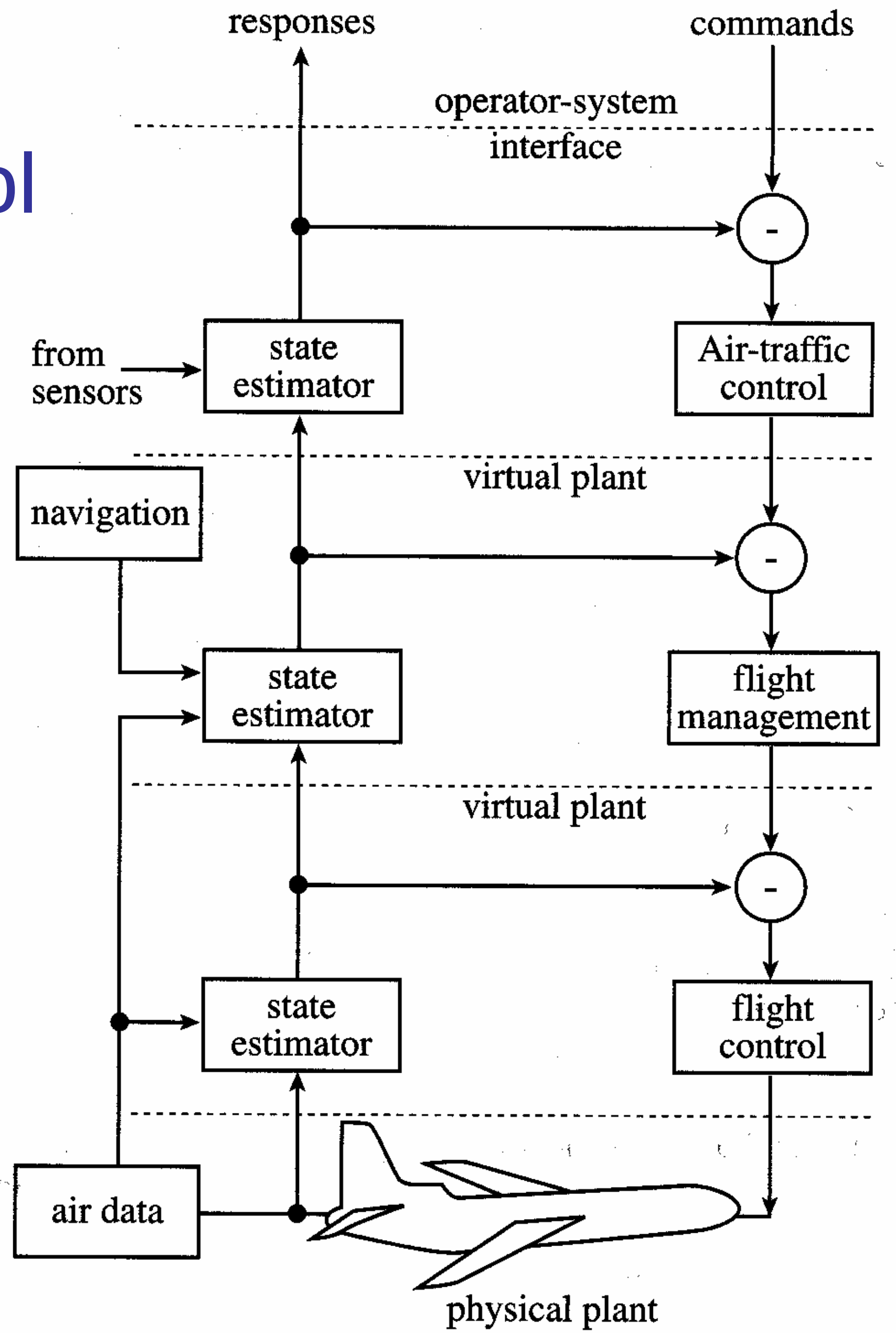

FIGURE 1–4 Air traffic/flight control hierarchy.

Robot control system

- Scenario planner
  - Rendezvous, repair plan for space robot
- Task planner
  - Chooses the sequence of assembly steps for assembly tasks
- Path/trajectory planner
  - Desired trajectory to be followed
- Manipulator controller
  - Track the desired trajectory via feedback control

1.2.2 Guidance and Control

- Flight management system
  - Optimization to find the most desirable trajectories
  - Constraints
    - Max/min. allowed cruise speed
    - Descent/ascent rates.
    - Ground track and altitude profile from air-traffic control
    - Weather conditions
  - Cost function
    - Minimum fuel consumption or
    - Minimum time control.
  - Optimal or heuristic solution. (in order of seconds/minutes).
  - Additional operator interaction.

1.2.3 Real-Time Command and Control

- Air Traffic Control (ATC) system – highest hierarchy.->
  - Generates and presents the information needed by the operators.
  - Provides voice and telemetry links to on-board avionics.
  - Less stringent timing requirements.
    - Keyboard and display: 10 Hz
    - Radar input: 1-2 sec
    - Weather update: 10 sec
    - Operator input: sporadic
  - Distributed system with networks.

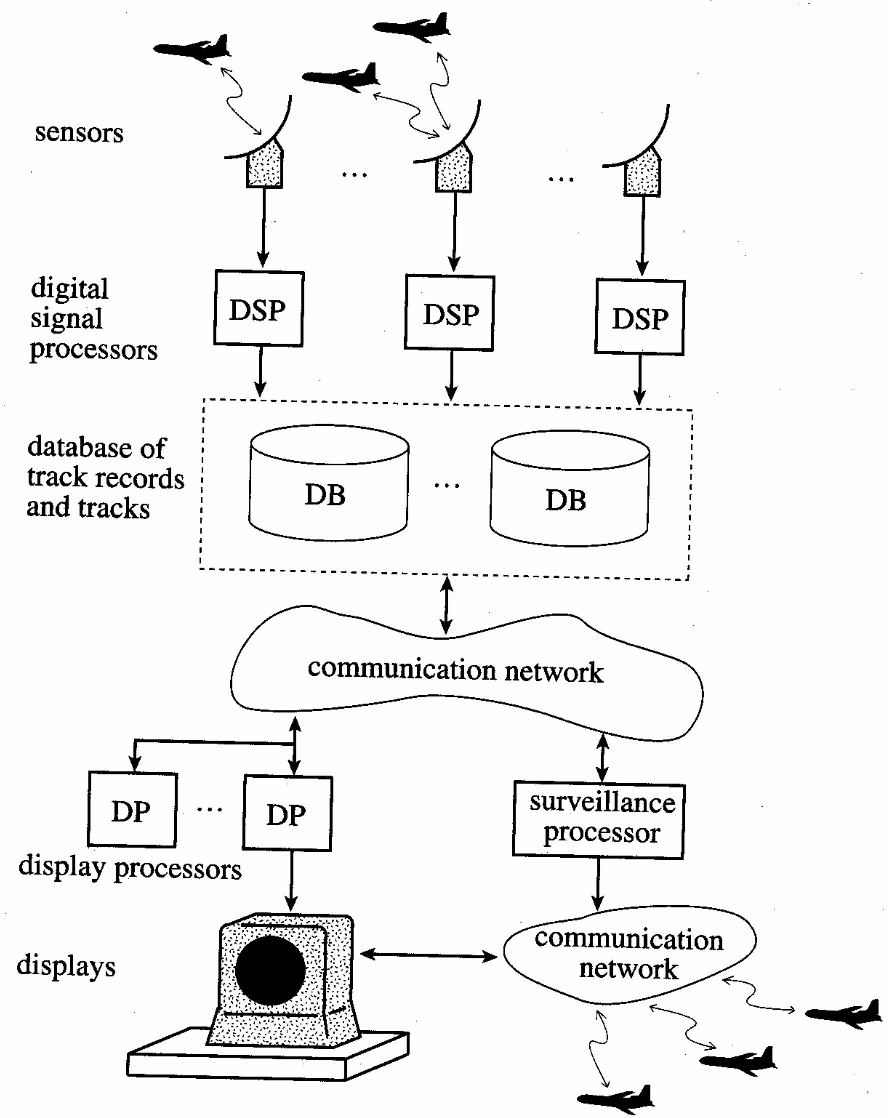

FIGURE 1–5 An architecture of air traffic control system.

1.3 Signal Processing
1.3.1 Processing Bandwidth Demands

- Real-time signal processing

$$x(k) = \sum_{i=1}^{m} a(k,i)x(k-i) + \sum_{j=1}^{n} b(k,j)y(k-j)$$

  - Time required: O(n)
  - Sampling rate kHz to 10 kHz:

$$10^4 \quad to \quad 10^7 \quad computations\ (mul/add)$$

- MPEG
  - Divide image into 8x8 image blocks

$$m^4 \rightarrow 64m^2 \quad mul\ /\ add$$

1.3.2 Radar System

- Passive radar signal processing and racking system ->
- Radar signal processing
  - Doppler shift – position and velocity track record
  - FFT O(n log n)
  - Phase array radar: electronic direction switching within msec. Multiple beam scanning.

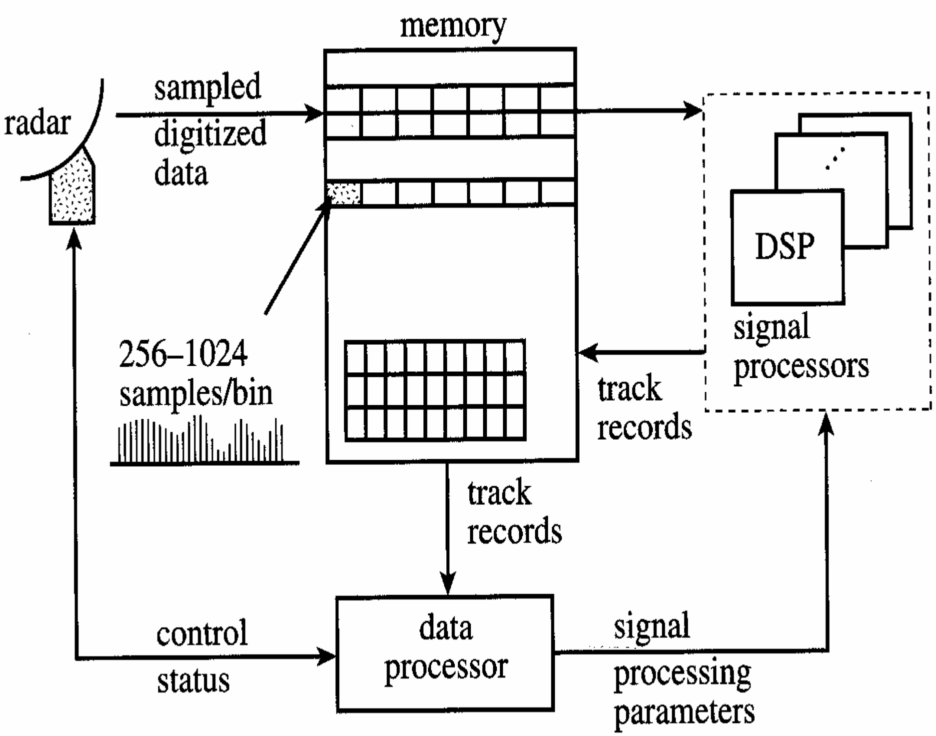

FIGURE 1-6 Radar signal processing and tracking system.

Tracking and Gating

- **Tracker**: Examine all track records to sort out false alarms and update trajectories of detected objects.
  - 1. **Gating**: process of sorting measured values into two categories (can/cannot assigned to established trajectories)
  - 2. **Data Association**:
    - Nearest neighbor algorithm.
    - Multiple hypothesis tracking algorithm.
- Data dependent complexity O(nm log nm)

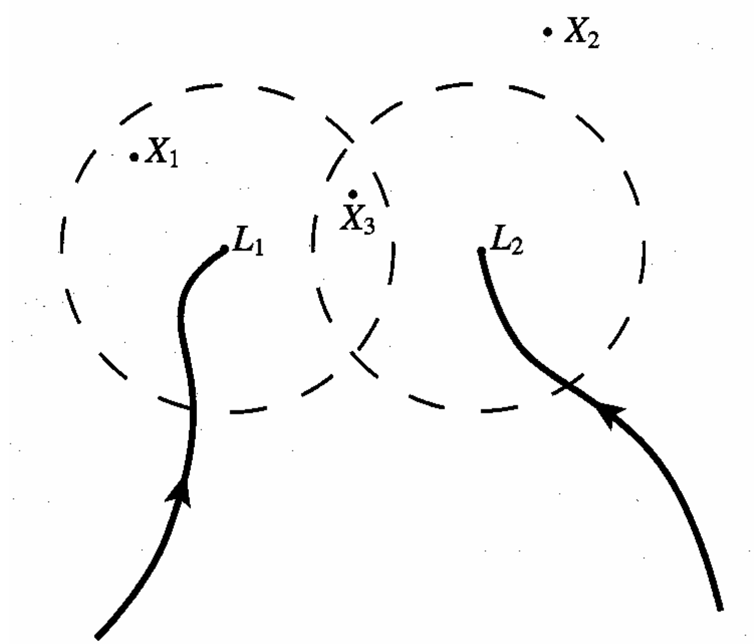

FIGURE 1–7 Gating process.

1.4 Other Real-Time Applications
1.4.1 Real-Time Database

- Contains **image objects**: Data objects representing real-world objects.
  - Updated periodically
  - Real-time data are perishable: Quality of data degrades.
    - **Age**: the length of time since the instant of the last update.
    - **Absolutely (temporally) consistent**: The maximum age of objects in the set is no greater than a certain threshold.
    - **Relatively consistent**: The maximum difference in ages of the objects in the set is no greater than the relative consistency threshold.
    - **Similarity**: Differences between the values is within an acceptable threshold from the perspective of every transaction that may read the object.
  - Application: air traffic control, aircraft mission, spacecraft control, process control.

1.4.2 Multimedia Applications

- Multimedia application: process, store, transmit, and display any number of video streams, audio streams, images, graphics, and text.

- **MPEG-2** Compression/Decompression:
  - Motion analysis and estimation
    - Consecutive video frames are not independent.
    - Divide each image into 16x16 major blocks for luminance
    - 8x8 blocks for chrominance components.
    - **I-frame (Intra-coded frame):** 1+9k frames encoded independent of other frames.
    - **P-frame (Predictive-coded frame):** 1+9k+3/6: Predicted image from previous I frame.
    - **B-frame (Bi-directionally predicted frame):** Predicted from both previous I/P-frame and subsequent P/I frame.

MPEG-2

- Direct Cosine Transform
  - 8x8 blocks transformed into frequency domain.
- Entropy encoding
  - Encode the as 2-tuples of (run length, value).
  - Variable-length and fixed-length code to further reduce the bit rate.
- Decompression
  - Produce a close approximation of original blocks with inverse transform.
  - Reconstruct the images in all frames from I/P/B-frames.
- Real-time characteristics
  - Computational-intensive process dependent on *frame rate* and *resolution*.
  - Lip synchronization within 80 msec.
  - *End-to-end response time* and *response time jitter* are important for interactive applications.

1.5 Summary

- Four types of real-Time applications
  - *Purely cyclic*: Most digital controllers.
    - Flight control system.
  - *Mostly cyclic*: Periodical, but also respond to some external events asynchronously.
    - Ex: Fault recovery and external commands
    - Modern avionics, process control systems.
  - *Asynchronous and somewhat predictable*: Duration between consecutive executions of a task may vary considerably, but with bounded ranges or known statistics.
    - Multimedia communication, radar signal processing.
  - *Asynchronous and unpredictable*: React to asynchronous events with high run-time complexity.
    - Intelligent real-time control systems.