Embedded Real-Time Systems: An Introduction

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Lecture #2

Goals of the Course

High-Level Goals

1. Understand the scientific principles and concepts behind embedded real-time systems, and
2. Obtain hands-on experience in programming embedded real-time systems.

By the end of the course, you must be able to

- Understand the "big ideas" in embedded real-time systems
- Obtain direct hands-on experience on both hardware and software elements commonly used in embedded real-time system design
- Understand basic real-time resource management theory
- Understand the basics of embedded real-time system application concepts such as signal processing and feedback control
- Understand, and be able to discuss and communicate intelligently about
  - I/O and device driver interfaces to embedded processors with networks and multimedia cards
  - OS primitives for concurrency, timeouts, scheduling, communication and synchronization

The Big Ideas

- HW/SW Boundary
- Non-processor-centric view of architecture
- Bowels of the operating system
  - specifically, the *lower* half of the OS
  - Concurrency
- Real-time scheduling
- Analyzability
  - how do you “know” that your drive-by-wire system will function correctly?
- Application-level techniques
  - signal processing, control theory

What *are* Embedded Systems anyway?

Based on Lecture by Prof. Koopman

Embedded Systems: An Introduction

- What is an embedded system?
  - More than just a computer
- What makes embedded systems different?
  - Real-time operation
  - *Many* sets of constraints on designs
    - size
    - cost
    - time
    - reliability
    - safety
    - energy
    - security
- What embedded system designers need to know?
  - The "big" picture
  - Skills required to be an "expert" in this area

What is an Embedded System?

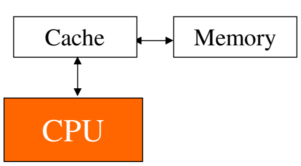
- Computer purchased as part of some *other/bigger* piece of equipment
  - Typically dedicated software (may be user-customizable)
  - Often replaces previously electromechanical components
  - Often no "real" keyboard
  - Often limited display or no general-purpose display device
- But, every system is unique: there are always exceptions

CPU: An All Too Common View of Computing

- Measured by:
  - Performance

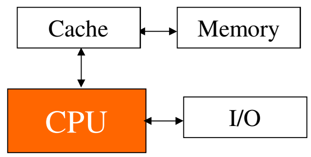
An Advanced Computer Engineer's View

- Measured by: Performance
  - Compilers matter too...



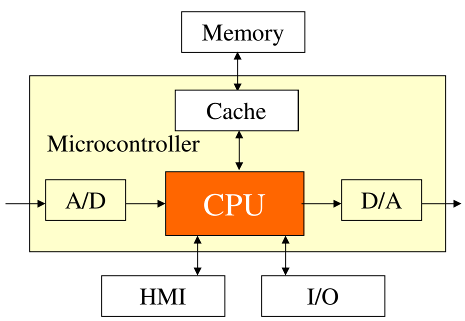
An Enlightened Computer Engineer's View

- Measured by: Performance, Cost
  - Compilers & OS matter



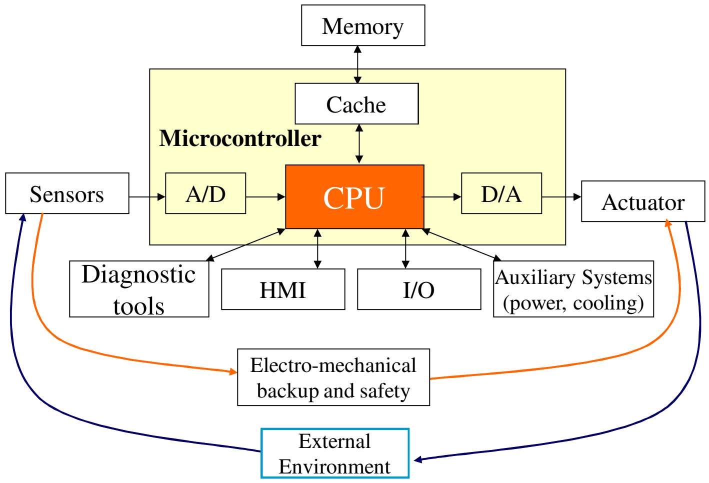
An Embedded Computer Designer's View

- Measured by: Cost, I/O connections, Memory Size, Performance



An Embedded Control System Designer's View

- Measured by:
  - Cost, Time-to-market, Cost, Functionality, Cost & Cost.

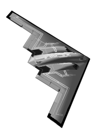
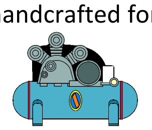


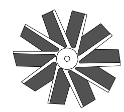
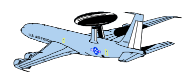
A Customer View

- Reduced Cost
- Increased Functionality
- Improved Performance
- Increased Overall Dependability

Some Embedded System Examples

- Pocket remote control RF transmitter
  - 100 KIPS, water/crushproof, fits in pocket, 5-year battery life
  - Software handcrafted for small size (less than 1 KB)
- Industrial equipment controller (e.g., elevator; jet engine)
  - 110 MIPS for 1 to 10 CPUs, 1 8 MB memory
  - Safetycritical software; realtime control loops
- Military signal processing (e.g., Radar/Sonar)
  - 1 GFLOPS, 1 GB/sec I/O, 32 MB memory
  - Software handcrafted for extremely high performance

Embedded Computers *Rule* the Marketplace

- ~100 Million PCs vs. ~5 Billion Embedded CPUs/microcontrollers annually
  - Embedded market growing; PC market *mostly* saturated
- Smartphones in gray area

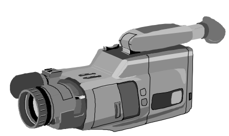
Why Are Embedded Systems Different?

Four General Categories of Embedded Systems

- "General" Computing
  - Applications *similar* to desktop computing, but in an embedded package
  - Video games, set-top boxes, wearable computers, automatic tellers
- Control Systems
  - Closed-loop feedback control of real-time system
  - Vehicle engines, chemical processes, nuclear power, flight control
- Signal Processing
  - Computations involving large data streams
  - Radar, Sonar, video compression
- Communication & Networking
  - Switching and information transmission
  - Telephone system, Internet connectivity

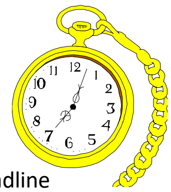
Types of Embedded System Functions

- Control Laws
  - PID control
  - Fuzzy logic, ...
- Sequencing logic
  - Finite state machines
  - Switching modes between control laws
- Signal processing
  - Multimedia data compression
  - Digital filtering
- Application-specific interfacing
  - Buttons, bells, lights,...
  - Highspeed I/O
- Fault response
  - Detection & reconfiguration
  - Diagnosis
- ...



Distinctive Embedded System Attributes

- **Reactive**: computations occur in response to external events
  - Periodic events (e.g., rotating machinery and control loops)
  - Aperiodic events (e.g., button closures)
- **Real-Time: timing correctness is part of system correctness**
  - "Hard" real-time
    - Absolute deadline, beyond which answer is useless
    - May include minimum time as well as maximum time
  - "Soft" real-time
    - Missing a deadline is not catastrophic
    - Utility of answer degrades with time difference from deadline
  - ***Example***:
    - a train is entering an urban area...
    - the railway gate in the city allows automotive traffic to go over the tracks
    - when should the railway gate close?



In general,

Real Time != "Real Fast"

Typical Embedded System Constraints

- Small Size, Low Weight (SWaP)
  - Handheld electronics
  - In transportation applications, weight costs money

- Low Power
  - Battery power for 8+ hours (laptops often last only 2 hours)
  - Limited cooling may limit power even if AC power available
- Harsh environment
  - Heat, vibration, shock
  - Power fluctuations, RF interference, lightning
  - Water, corrosion, physical abuse

- Safety-critical operation
  - Must function correctly
  - Must *not* function incorrectly
- Extreme cost sensitivity
  - $.05 adds up over 10,000,000 units

Embedded System Design World View

A complex set of tradeoffs:

- Optimize for ***more than just speed***
- Consider ***more than just the computer***
- Take into account ***more than just initial product design***

Multi-Discipline X **Multi-Objective** X **Multi-Phase**

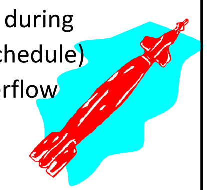
Multi-Discipline
- Electronic Hardware
- Software
- Mechanical Hardware
- Control Algorithms
- Humans
- Society/Institutions

Multi-Objective
- Dependability
- Affordability
- Safety
- Security
- Scalability
- Timeliness

Multi-Phase
- Requirements
- Design
- Manufacturing
- Deployment
- Logistics
- Retirement

Mission-Critical Applications Require Robustness

- **Loss of Arianne inaugural flight in June, 1996**
  - Lost a $400 million scientific <u>payload</u> (the rocket was *extra*)
- **Efforts to reduce system costs led to the failure**
  - Reuse of Inertial Reference System software from Ariane 4
  - Improperly handled exception caused by variable overflow during new flight profile (that wasn't simulated because of cost/schedule)
  - 64-bit `float` converted to 16-bit `int` assumed not to overflow
    - Exception caused dual hardware shutdown (software doesn't fail!)

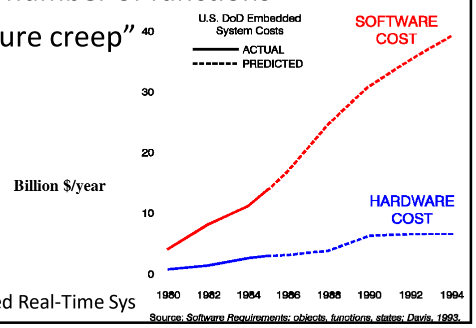


- **What really happened?**
  - The narrow view: it was a software bug – fix it
  - The broader/correct view: the loss was caused by a lack of system robustness in an exceptional (unanticipated) situation

Many embedded systems must be robust

Software Drives Designs

- Hardware is mostly a recurring cost
  - Cost proportional to number of units manufactured
- Software is a “one-time” non-recurring engineering design cost (NRE)
  - Paid for “only once”
    - But bug fixes may be expensive, or even impossible
  - Cost is related to complexity & number of functions
  - Market pressures lead to “feature creep”
- **Software Is NOT free!!!!!**



Life-Cycle Concerns Figure Prominently

- “Let's use a CAD system to re-synthesize designs for cost optimization”
  - Automatically use whatever components are cheap that month
  - Would permit quick responses to bids for new variants
  - Track record of working fine for PC motherboards
- Why wouldn't it work for an automotive application?
  - Embedded systems had more analog than digital mostly digital synthesis tools
  - Cost of re-certification for safety, FCC, warrantee repair rate
  - Design optimized for running power, not idle power
    - Car batteries must last a month in a parking lot
  - Parts cost did not take into account lifecycle concerns
    - Price breaks for large quantities
    - Inventory, spares, end-of-life buy costs
  - Tools didn't put designs on a single sheet of paper
    - Archive system: paper-based how else do you read
  - 20-year old files? Could even be 40 years old!

Embedded System Designer Skill Set

- Appreciation for **multi-disciplinary** nature of design
  - Both hardware & software skills
  - Understanding of engineering beyond digital logic
  - Ability to take a project from specification through production
- Communication & **teamwork** skills
  - Work with other disciplines, manufacturing, marketing
  - Work with customers to understand the real problem being solved
  - Make a good presentation; even better write ``trade rag'' articles
- And, by the way, **technical skills** too...
  - *Low-level*: Microcontrollers, FPGA/ASIC, assembly language, A/D, D/A
  - *High-level*: Object-oriented Design, C/C++, Real Time Operating Systems
  - *Meta-level*: Creative solutions to highly constrained problems
  - *Likely* : **U**nified **M**odeling **L**anguage, embedded networks
  - *Possibly*: Java, Android, iOS, Windows Mobile

Real-Time Systems

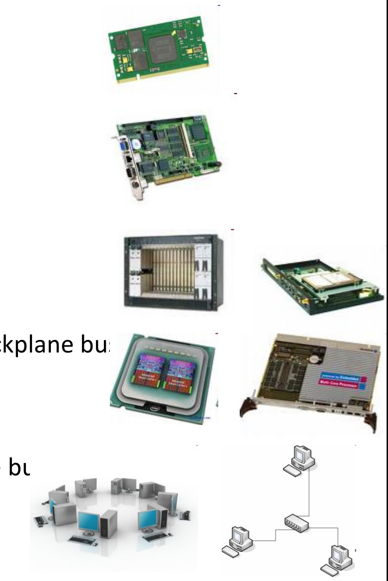
- The correctness of a real-time system is comprised of **both logical correctness and timeliness of results**

Application Domains (Example Applications)

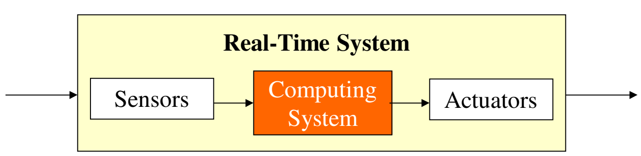
- Process Control (Chemical Plants)
- Factories (Automotive Assembly Plants)
- Supervisory Control and Data Acquisition (Utilities)
- Medical Devices and Healthcare (Medical Robots and Equipment)
- Computer Peripherals (Laserprinters)
- Automotive (Engine controls)
- Telecommunications (Cellphone Infrastructure)
- Aerospace (avionics)
- Internet and Multimedia (Videoconferencing, IP-TV, Skype)
- Consumer Electronics (Mobile phones, TVs, set=top boxes)
- Military systems (missile guidance systems, radar systems)
- Space systems (platenary rovers, rockets, satellites)

Processors in Embedded Real-Time Systems

- Uniprocessors
  - 4-bit microcontrollers
  - 8-bit microcontrollers
  - 16-bit microcontrollers
  - 32-bit microcontrollers
  - 64-bit microcontrollers
  - 128-bit microcontrollers
- Multiple processors
  - Multiple single-board computers on a backplane bu
- Multicore processors
  - Multicore processors
  - Multiple multicore boards on a backplane bu
- Networks of computers
- Networks of multi-processor systems



Generic Model



Physical Environment

Typical Characteristics of Real-Time Systems

- Timing constraints
- Embedded nature
- Safety criticality
- Concurrency
- Distributed nature
- Reactive/Feedback system
- Stability
- Exception handling
- Reliability

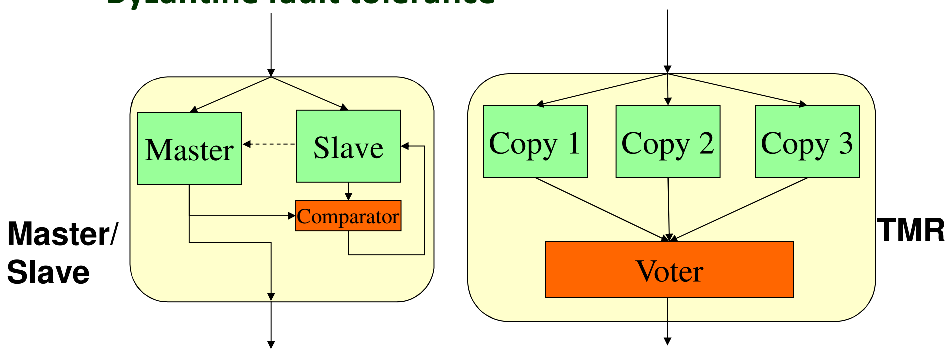
There are always exceptions….

Approaches to Reliability/Fault-Tolerance

- Error Avoidance
- Error detection and removal
- Hardware Fault-Tolerance
- Software fault-tolerance

Hardware Fault-Tolerance

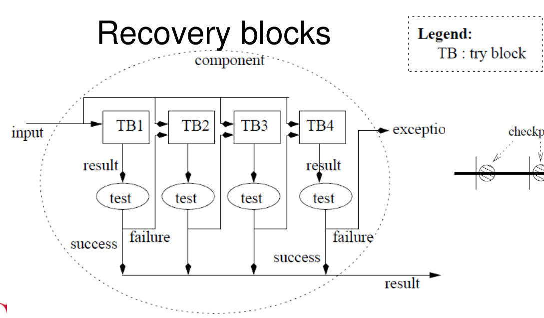
- Built-in Self Testing
- Replication techniques
  - **Master-Slave** (Primary-Backup Systems)
  - **T**riple **M**odular **R**edundancy (TMR) with Voting
- **Byzantine fault tolerance**

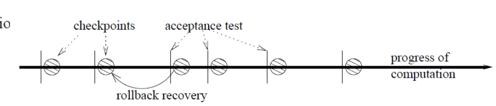


Software Fault-Tolerance

- *N*-version programming:
  - Multiple versions developed in parallel
- Recovery blocks
  - Try execution, test for correctness, else try another path
- Checkpointing and rollback
- Analytical redundancy
  - Compute same or similar function using other techniques

Recovery blocks





Checkpointing/Rollback

Points in Time

- **Events** represent occurrences in time
- Events can be **periodic** or **aperiodic**
  - Periodic events have a periodic arrival pattern
  - A recurring event without a periodic pattern is called an aperiodic event
- Event sources can be **internal** or **external**
  - Internal events are generated from within the real-time system
    - E.g. timeouts, task completions, lock releases, watchdog timers
  - External events are generated by the environment
    - E.g. a user pressing a button, water leaks, temperature getting too hot (or cold)

Types of Timing Constraints

- **Deadlines (the most common):** action must be taken/completed before a specific instant of time
  - **Hard deadlines**: timing constraints must be met, or else system failure can result
    - E.g. Flight controls
  - **Soft deadlines**: timing constraints must be met when possible; else, the desirability of the system drops but no major damage occurs
    - E.g. internet audio/video conferencing
  - **Firm deadlines**: timing constraints must be met as much as possible with an occasional miss acceptable
    - E.g.
- **Delays**
  - Minimum delay between events

Review

- Embedded system and perspectives
- Real-time systems and characteristics
  - Types of fault-tolerance
  - Events and types

- Coming next: uniprocessor scheduling