Implementing a Fault Tolerant Real-Time Operating System

EEL 6686: Presentation 2

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Introduction

- What is a real-time operating system (RTOS)?
  - OS that guarantees a certain functionality within specified time constraints
  - Link between software and embedded system
- Main roles:
  - Task management - scheduling and priorities
  - Time management - timing constraints, delays, time outs
  - Dynamic memory allocation - file creations, protections
  - Interprocess communication and synchronization - keeps data intact
- RTOS need valid results both in correctness and in specified amount of time
  - Incorrect results would result in a failure
  - Not meeting timing constraints also results in a failure

Specifications

- Should be able to react to external stimuli in timely fashion
- Emphasize predictability efficiency
- Soft deadline
  - Results in degraded performance if deadline is missed
  - Result still has utility after deadline
  - Example: Video streaming, anything with human interactions
- Firm deadline
  - Result has no utility after deadline
  - Hard deadline if missing deadline causes a catastrophic event
  - Example: Automation, medical systems

Fault Tolerant RTOS

- Some form Fault tolerance is necessary in everyday systems
- Problem: Fault tolerance usually comes with overhead
  - Design a very fault tolerant system?
    - Less failures in general but for RTOS does it really?
    - Introduces more timing constraints
    - For RTOS if deadline is not met considered a failure
  - No fault tolerance?
    - Can meet timing constraints much easier
    - If there is a fault it can also lead to system failure
    - Faults can cause bad results which cause more timing issues
- Need good balance

Fault Mitigation Techniques

- Traditional fault tolerant systems include redundancy
- Some common ones seen include:
  - Processor
    - Triple modular redundancy (TMR)
    - If one input is wrong, it is masked by voting system
  - Fault tolerance in algorithms
    - Error correction codes for data
  - Timing redundancy for transient errors
  - Memory
    - Dynamic storage allocation
    - Redundancy of disk or error correction codes
- Other considerations must be made for operating systems
- What are some fault tolerant techniques for RTOS?

Mitigation Techniques for OS (1/2)

Some examples of techniques to make OS more fault tolerant:

- Kernel Considerations
  - Should be able to communicate to supervisor to correct errors
  - Event logging to determine where error happened
  - Protection against bad system calls
- Interrupt handling
  - Should be predictable for fault tolerance
  - All services should be able to save state and execute to prioritize higher interrupts
- Memory management units
  - Some RTOS disable for higher speed
  - Everything is run on same address space not recommended
- I/O management
  - Active spares in order to not waste time

Mitigation Techniques for OS (2/2)

- Many different ways to make an OS fault tolerant
  - Cannot implement all techniques due to size/timing constraints
  - Implementations increase timing, increases chance of failure
- What to make redundant?
  - Options are limited for hard deadlines
  - Need to pick out critical functions of RTOS
  - Make only critical functions fault tolerant
  - What method to use for least timing overhead?

Critical Functionality of RTOS

Scheduling and resource allocation considered important for RTOS

- Manage resources efficiently to stay within timing constraints
- Scheduling algorithms
  - Rate monotonic - static scheduling defined in advance
  - Earliest deadline first - dynamic scheduling
  - Least laxity first - based on slack (amount of time left)
- N-copy scheduler
  - Copied n times and run simultaneously
  - Results are voted for at the end
  - Least amount of timing overhead
- Checkpointing
  - Go back to a previous known state
  - bad timing overhead
  - better hardware overhead
- Making scheduler and resource allocation fault tolerant can make sure timing constraints are met

Introduction and Implementation of a fault tolerant resource manager using ARINC 653 and RTEMS

- Process and Tread Management
  - RTOS should activate a process once and release it once
  - Each activate and release must start on time and finish before its deadline
  - RTOS must guarantee the availability of resources for required process

Possible fault due to careless management of resources

- If tasks behavior are not monitored they may execute carelessly
- Careless or malicious executions could eat up precious resources
- This could exhaust system resources

Example

- A fault in an application could create too many tasks
- Other tasks fail because of their inability to acquire resources
- Fault tolerant RTOS resource manager must exist to prevent such scenarios

Solution 1:

- Determine a process's maximum allowable resource usage before execution
- Processes are not allowed to use more than their reserved resources
- Processes wanting more than allowed are discarded as error

Solution 2: Fixed -priority systems ARINC 653

- Process manager runs partitions or address spaces, according to a timeline provided by the designer
- Each address space is placed into one or more windows of execution in a hyper period
- Tasks within an address space are selected and executed, while others a rejected
- Hard/Critical Processes are guaranteed their required resources
- Soft/normal processes are rejected

ARINC 653 Architecture 1

- Application software layer separates applications into partitions
- Services are routed through the Application Executive Interface
- Containment of faults from each partition must be ensured by the core software layer

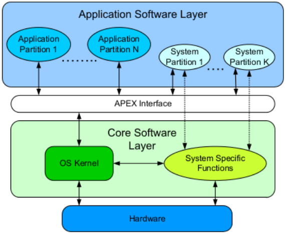


Figure 1. Standard ARINC 653 System Architecture

ARINC 653 terminology

- Spatial Partitioning: ensures one application or partition does not access anothers memory space
- Temporal Partitioning: ensures that the activities of one partition do not affect the timing of another

ARINC 653 Implementation using RTEMS

- AIR innovation initiative sponsored by ESA creators of the ARINC 653 architecture based on RTEMS
- Current available ARINC 653 implementations are commercial and very expensive
- Example: X-47B unmanned aerial vehicle owner US Air Force

RTEMS Kernel Architecture 1

- Designed to support application with real time requirements while maintaining a compatible interface with open standards
  - Multitasking capabilities
  - Event-driven, priority-based, preemptive scheduling
  - comprehensive mechanism for inter-task communication and synchronization
  - high degree of user configurability
  - supports homogeneous and heterogeneous multiprocessor system architectures

RTEMS Kernel Architecture 2

- RTEMS does not provide all the required mechanisms for ARINC 653
- However, RTEMS does meet the basis for a deployment of ARINC 653 services
- RTEMS resource manager form the executive interface presented to the application

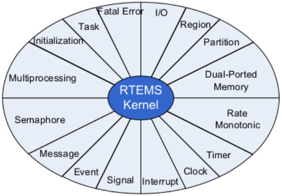


Figure 2. The RTEMS resource managers

RTEMS Kernel Architecture 3

- From the point of view of its internal architecture RTEMS provides a set of layered components that provide a set of services to real-time applications
- RTEMS is a robust multitasking operating system kernel
- RTEMS can support a wide range of processors through an adaptor layer that is independent of hardware known as a board support package

AIR System Architecture 1

- The AIR architecture preserves the hardware and and RTOS independence
- AIR adds modules to the RTOS kernel to include spatial and temporal partitioning which are:
  - AIR partition scheduler
    - Determines who owns the resource at a given time, ensures temporal segregation
  - AIR partition dispatcher
    - Saves and restores execution content for the heir partitions and guarantees spatial segregation
  - AIR inter-partition communication module
    - Allow coms between different partitions without violating spatial segregation

AIR System Architecture 2

- ARINC 653 application executive interface (APEX) furnishes the following set of services using the AIR architecture
  - partition management
  - process management
  - time management services
  - inter-partition communication services
  - intra-partition communication services
  - Health monitoring

AIR System Architecture Overview

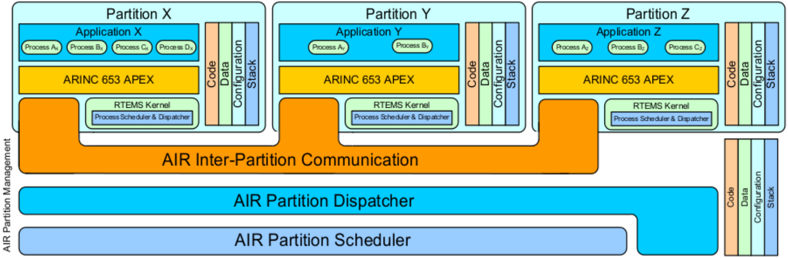


Figure 3. Overview of the AIR System Architecture

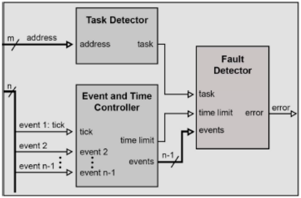
Hardware Scheduler (Hw-S)(1/2)

- Focuses on task management of an RTOS
- Hardware implementation to detect faults affecting apps
- Aims to detect faults causing:
  - Sequence errors - scheduling failures
  - Timing errors
- Assumptions for hardware scheduler:
  - Scheduler is required part that defines when to execute task
  - Algorithm is deterministic
  - Tasks implemented by programs stored in specific memory location
  - Tasks behavior follows set of time constraints and defined by external events

Hardware Scheduler (Hw-S)(2/2)

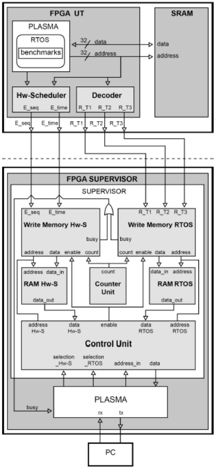
Split into 3 blocks

- Task detector
  - Based on info stored in addr table
  - Generated during compile time
  - Identifies tasks in execution
  - Reads address accessed by microp
  - Compares with records in addr table
- Event and time controller
  - Defines time limit deadline
  - Detects events that change exe. time
- Fault detector
  - Implements the scheduling algorithm
  - Fault detection based on task in exe.



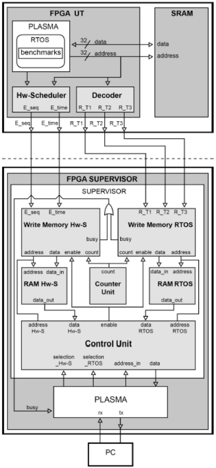
Validation (1/2)

- Testing Hw-S developed using FPGA
  - Comparing detection with RTOS vs Hw-S
  - 2 FPGAs used to gather results
  - Identifies tasks in execution
- Using Xilinx Spartan Model XC3S500E
- split into 2 parts
- FPGA under test (UT)
  - Inject faults into this device
- FPGA supervisor
  - Stores results
  - sets up fault injection campaigns



Validation (2/2)

- FPGA UT is Composed of:
  - Hw-S unit that was developed in this paper
  - 32 bit RISC plasma processor running app.
  - Unit to decode address associated to task
- FPGA supervisor composed of:
  - Control unit which receives control signals
  - RAM unit to store execution flows from Hw-S and RTOS
  - Write memory units for storing errors
  - Counter unit to indicate when data is stored



Fault Injection Setup

- Two benchmarks were tested with 3 tasks each
  - Task 1 (T1), Task 2 (T2), and Task 3 (T3) access and update 3 different global values
  - T1 sends value to queue and T2 reads value and T3 writes value to global
- Fault injection done by applying voltage dips to FPGA UT
  - Injected with 0.3Mhz frequency

Results(1/2)

- Five types of behaviors were reported with fault injections
  - System works normally
  - Generates different types of errors which were 100% detected
  - Generates different types of errors presents different fault detection capability
  - Crashes and needs to be reset
  - FPGA configuration failure
- Hw-S was able to detect 100% of transient faults injected for all benchmarks

TABLE III. FAULT COVERAGE ASSOCIATED TO BM1

System behavior	Voltage range [mV]	Voltage Dips [%]	Fault coverage [%]	
			RTOS	Hw-S
Behavior_1	[1200-956]	20.34	-	-
Behavior_2	[955-943]	21.42	100.00	100.0
Behavior_3	[942-858]	28.50	69.00	100.00
Behavior_4	[857-651]	45.75	0.00	100.00
Behavior_5	[650-0]	100.00	-	-

(a)

TABLE IV. FAULT COVERAGE ASSOCIATED TO BM2

System behavior	Voltage range [mV]	Voltage Dips [%]	Fault coverage [%]	
			RTOS	Hw-S
Behavior_1	[1200-1120]	6.67	-	-
Behavior_2	[1119-893]	25.58	100.00	100.0
Behavior_3	[892-858]	28.50	56.00	100.00
Behavior_4	[857-651]	45.75	0.00	100.00
Behavior_5	[650-0]	100.00	-	-

(b)

Results (2/2)

- After 15% dips in voltage RTOS can no longer detect
  - Due to loss of information because the voltage dip is too high
- Scheduling error most common
- Four behaviors were found:
  - Microp went to wrong task
  - Remained executing only one task
  - Same task was repeated
  - Same task was repeated and next task was skipped
- Hw-S performed more robust when exposed to voltage dips
- Area overhead was only 10.07%

Future works

- Hw-S
  - Voltage dips were only form of fault injection
  - Limited benchmarks
- ARINC 653
  - Health monitor is currently designed to only diagnosis system malfunctions and requires a ground maintenance crew for repairs
  - However, in a space environment the health monitoring services should have major adaptations and added complexity as human assistance is probably not available
  - No test data was presented in the use of AIR with RTEMS to demonstrate the systems reliability

References

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