Software Quality Engineering

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Testing, Quality Assurance, and Quantiable Improvement
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Tian Siyuan tiansiyuan@gmail.com

Chapter 16. Fault Tolerance and Safety Assurance

- Basic Concepts
- Fault Tolerance via RB and NVP
- Safety Assurance Techniques/Strategies
- Summary and Perspectives

QA Alternatives

- Defect and QA
    - Defect: error/fault/failure
    - Defect prevention/removal/containment
    - Map to major QA activities
- Defect prevention
    - Error source removal & error blocking
- Defect removal: Inspection/testing/etc.
- Defect containment | This Chapter
    - Fault tolerance

      local faults <> system failures

    - Safety assurance: contain failures or weaken failure-accident link

QA and Fault Tolerance

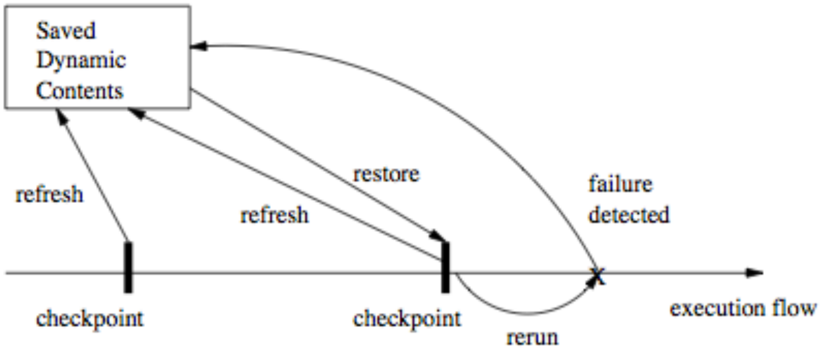
- Fault tolerance as part of QA
    - Duplication: over time or components
    - High cost, high reliability
    - Run-time/dynamic focus
    - FT design and implementation
    - Complementary to other QA activities
- General idea

- Local faults not lead to system failures
- Duplication/redundancy used
- redo) recovery block (RB)
- parallel redundancy

  => N version programming (NVP)

- Key reference (Lyu, 1995b): M.R. Lyu, S/w Fault Tolerance, Wiley, 1995.

FT: Recovery Blocks

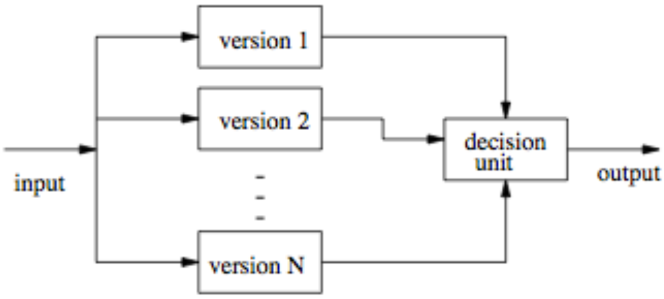


- General idea: Fig 16.1 (p.270)
  - Periodic checkpointing
  - Problem detection/acceptance test
  - Rollback (recovery)

FT: Recovery Blocks

- Periodic checkpointing
  - too often: expensive checkpointing
  - too rare: expensive recovery
  - smart/incremental checkpointing
- Problem detection/acceptance test
  - exceptions due to in/ex-ternal causes
  - periodic vs event-triggered
- Recovery (rollback) from problems
  - external disturbance: environment?
  - internal faults: tolerate/correct?

FT: NVP



- FT with NVP: Fig 16.2 (p.272)
  - NVP: N-Version Programming
  - Multiple independent versions
  - Dynamic voting/decision) FT.

FT: NVP

- Multiple independent versions
  - Multiple: parallel vs backup?
  - How to ensure independence?
- Support environment
  - concurrent execution
  - switching
  - voting/decision algorithms
- Correction/recovery?
  - p-out-of-n reliability
  - in conjunction with RB
  - dynamic vs. off-line correction

FT/NVP: Ensure Independence

- Ways to ensure independence
  - People diversity: type, background, training, teams, etc.
  - Process variations
  - Technology: methods/tools/PL/etc.
  - End result/product
    - design diversity: high potential
    - implementation diversity: limited
- Ways to ensure design diversity
  - People/teams
  - Algorithm/language/data structure
  - Software development methods

    - Tools and environments
    - Testing methods and tools (!)
    - Formal/near-formal specifications

FT/NVP: Development Process

- Programming team independence
    - Assumption: P-team independence

      => version independence

    - Maximize P-team isolation/independence
    - Mandatory rules (DOs & DON'Ts)
    - Controlled communication (see below)
- Use of coordination team
    - 1 C-team - n P-teams
    - Communication via C-team
        - not P-team to P-team
        - protocols and overhead cost
    - Special training for C-team
- NVP-specific process modifications

FT/NVP: Development Phases

- Pre-process training/organization
- Requirement/specification phases
    - NVP process planning
    - Goals, constraints, and possibilities
    - Diversity as part of requirement
        - relation to and trade-off with others
        - achievable goals under constraints
    - Diversity specification
    - Fault detection/recovery algorithm?
- Design and coding phases: enforce NVP-process/rules/protocols

FT/NVP: Development Phases

- Testing phases
    - Cross-checking by different versions

      -- free oracle!

    - Focus on fault detection/removal
    - Focus on individual versions
- Evaluation/acceptance phases
    - How N-versions work together?
    - Evidence of diversity/independence?
    - NVP system reliability/dependability?
    - Modeling/simulation/experiments
- Operational phase
    - Monitoring and quality assurance
    - NVP-process for modification also

FT and Safety

- Extending FT idea for safety
    - FT: tolerate fault
    - Extend: tolerate failure
    - Safety: accident free
    - Weaken error-fault-failure-accident link
- FT in SSE (software safety engineering)
    - Too expensive for regular systems
    - As hazard reduction technique in SSE
    - Other related SSE techniques
        - general redundancy
        - substitution/choice of modules
        - barriers and locks
        - analysis of FT

What Is Safety?

- Safety: The property of being accident-free for (embedded) software systems.
    - Accident: failures with severe consequences
    - Hazard: condition for accident
    - Special case of reliability
    - Specialized techniques
- Software safety engineering (SSE)
    - Hazard identification/analysis techniques
    - Hazard resolution alternatives
    - Safety and risk assessment
    - Qualitative focus
    - Safety and process improvement

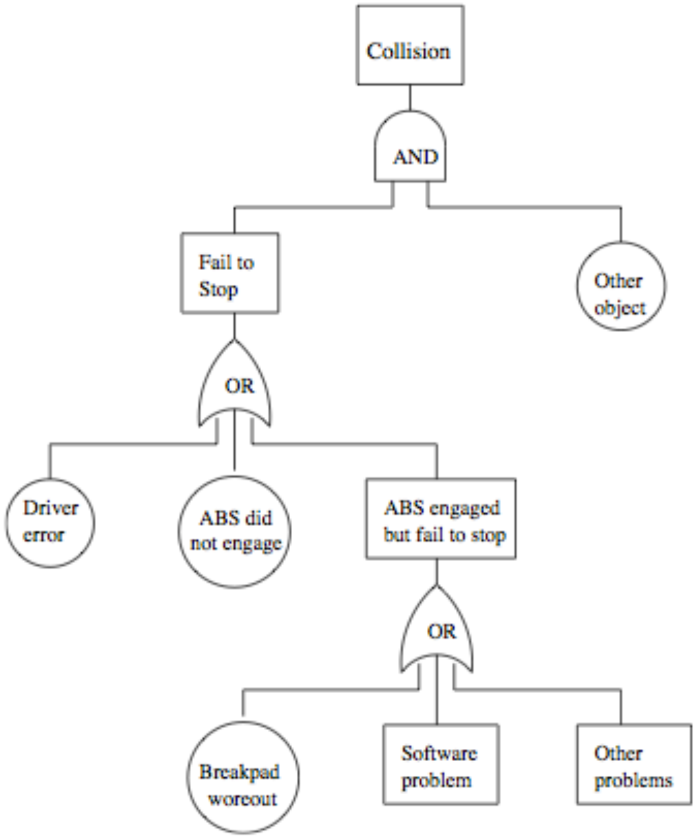
Safety Analysis & Improvement

- Hazard analysis
  - Hazard: condition for accident
  - Fault trees: (static) logical conditions
  - Event trees: dynamic sequences
  - Combined and other analyses
  - Generally qualitative
  - Related: accident analysis and risk assessment
- Hazard resolution
  - Hazard elimination
  - Hazard reduction
  - Hazard control
  - Related: damage reduction

Hazard Analysis: FTA

- Fault tree idea
  - Top event (accident)
  - Intermediate events/conditions
  - Basic or primary events/conditions
  - Logical connections
  - Form a tree structure
- Elements of a fault tree
  - Nodes: conditions and sub-conditions
    - terminal vs. no terminal
  - Logical relations among sub-conditions
    - AND, OR, NOT
  - Other types/extensions possible

Hazard Analysis: FTA Example



- Example FTA for an automobile accident (Fig. 16.3, p.276)

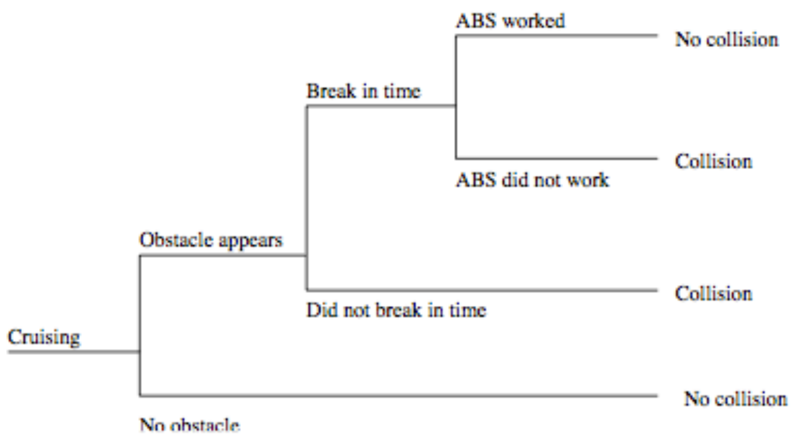
Hazard Analysis: FTA

- FTA construction
    - Starts with top event/accident
    - Decomposition of events or conditions
    - Stop when further development not required or not possible (atomic)
    - Focus on controllable events/elements
- Using FTA
    - Hazard identification
        - logical composition
        - (vs. temporal composition in ETA)
    - Hazard resolution (more later)
        - component replacement etc.
        - focused safety verification
        - negate logical relation

Hazard Analysis: ETA

- ETA: Why?
  - FTA: focus on static analysis
    - (static) logical conditions
  - Dynamic aspect of accidents
  - Timing and temporal relations
  - Real-time control systems
- Search space/strategy concerns
  - Contrast ETA with FTA
    - FTA: backward search
    - ETA: forward search
  - May yield different path/info.
  - ETA provide additional info.

Hazard Analysis: ETA Example



- Example ETA for an automobile accident (Fig 16.4, p.277)
- Compare/contrast with FTA a few slides back

Hazard Analysis: ETA

- Event trees
  - Temporal/cause-effect diagram
  - (Primary) event and consequences
  - Stages and (simple) propagation

        - not exact time interval
        - logical stages and decisions
- Event tree analysis (ETA)
    - Recreate accident sequence/scenario
    - Critical path analysis
    - Used in hazard resolution (more later)
        - esp. in hazard reduction/control
        - e.g. creating barriers
        - isolation and containment

Hazard Elimination

- Hazard sources identification => elimination

  (Some specific faults prevented or removed.)

- Traditional QA (but with hazard focus)
    - Fault prevention activities
        - education/process/technology/etc
        - formal specification & verification
    - Fault removal activities
        - rigorous testing/inspection/analyses
- "Safe" design: More specialized techniques
    - Substitution, simplification, decoupling
    - Human error elimination
    - Hazardous material/conditions#

Hazard Reduction

- Hazard identification) reduction

  (Some specific system failures prevented or tolerated)

- Traditional QA (but with hazard focus)
    - Fault tolerance
    - Other redundancy
- "Safe" design: More specialized techniques
    - Creating hazard barriers
    - Safety margins and safety constraints
    - Locking devices
    - Reducing hazard likelihood
    - Minimizing failure probability
    - Mostly "passive" or "reactive"

Hazard Control

- Hazard identification) control
    - Key: failure severity reduction
    - Post-failure actions
    - Failure-accident link weakened
    - Traditional QA: not much, but good design principles may help
- "Safe" design: More specialized techniques
    - Isolation and containment
    - Fail-safe design & hazard scope#
    - Protection system
    - More "active" than "passive"
    - Similar techniques to hazard reduction
        - but focus on post-failure severity decrease vs. pre-failure hazard likelihood decrease

Accident Analysis & Damage Control

- Accident analysis
    - Accident scenario recreation/analysis
        - possible accidents and damage areas
    - Generally simpler than hazard analysis
    - Based on good domain knowledge

      (not much software specifics involved)
- Damage reduction or damage control
    - Post-accident vs. pre-accident hazard resolution
    - Accident severity reduced
    - Escape route
    - Safe abandonment of material/product/etc.
    - Device for limiting damages

Software Safety Program (SSP)

- Leveson’s approach (Leveson, 1995)

  -- Software safety program (SSP)
- Process and technology integration
    - Limited goals
    - Formal verification/inspection based
    - But restricted to safety risks

- Based on hazard analyses results
- Safety analysis and hazard resolution
- Safety verification
    - few things carried over
- In overall development process
    - Safety as part of the requirement
    - Safety constraints at different levels/phases
    - Verification/refinement activities
    - Distribution over the whole process

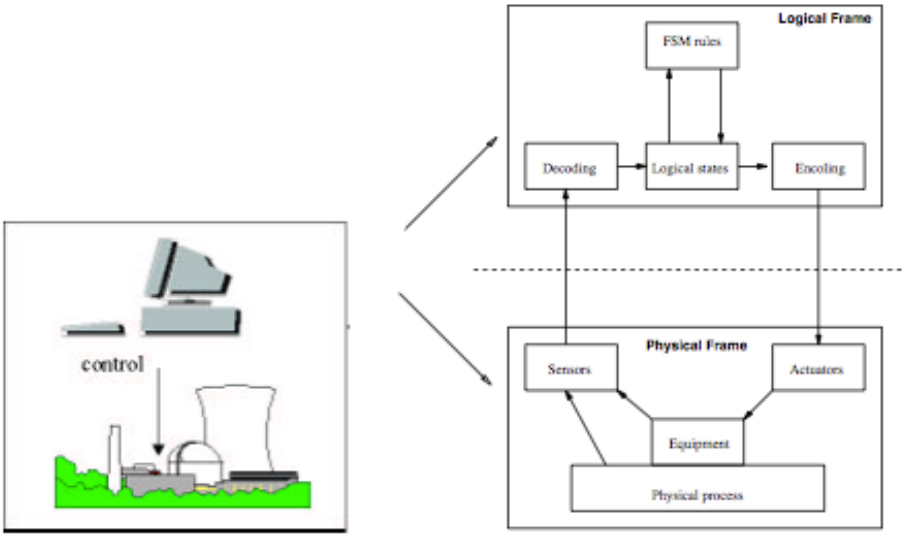
Case Study: PSC for CCSCS

- Object of study and general problems
    - CCSCS: Computer-controlled safety-critical systems
    - Problem: Safety and failure damage
    - (software) reliability models unsuitable
        - assuming large numbers of failures
        - missing damage information
    - Formal verification
        - static vs. dynamic verification
        - need systematic assertion derivation
- Prescriptive specification checking
    - Analyze sources of hazard
    - Derive systematic assertions
    - Dynamically check the assertions

TFM: Two-Frame-Model

- TFM: Two-Frame-Model
    - Physical frame
    - Logical frame
    - Sensors: physical => logical
    - Actuators: logical => physical
- TFM characteristics and comparison
    - Interaction between the two frames
    - Nondeterministic state transitions and encoding/decoding functions
    - Focuses on symmetry/consistency between the two frames

TFM Example



- TFM Example: Fig 16.5 (p.280)
    - physical frame: nuclear reactor
    - logical frame: computer controller

Usage of TFM

- Failure/hazard sources and scenarios
    - Hardware/equipment failures
    - Software failures
    - Communication/interface failures
    - Focus on last one, based on empirical evidence
- Causes of communication/interface hazards
    - Inconsistency between frames.
    - Sources of inconsistencies
    - Use of prescriptive specifications (PS)
    - Automatic checking of PS for hazard prevention

Frame Inconsistencies

- System integrity weaknesses: Major sources of frame inconsistencies in CCSCS
- Discrete vs. continuous
    - Logical frame: discrete
    - Physical frame: mostly continuous
    - Continuous regularity or validity of in-/extrapolation
- Total vs. partial functions
    - Logical frame: partial function

- Physical frame: total function
-) coercion, domain/default specs, etc.

Frame Inconsistencies (II)

- Invariants and limits
  - Logical frame: no intrinsic invariant
  - Physical frame: intrinsic invariant
  - Special case: physical limit
  -) assertions on boundaries/relations as invariants/limits to check
- Semantic gap
  - Logical frame: image/map of the reality
  - Physical frame: physical reality
  - Syntax vs. semantics in logical frame
- General solution: to derive systematic assertions for each integrity weakness and automatically/dynamically check them

Prescriptive Specifications (PS)

- Definition and examples
  - Assertion: desired system behavior
  - Use PS in CCSCS
- PS for CCSCS
  - Address integrity weaknesses
  - Systematic derivation
  - How to check? dynamic/automatic
  - Applications in case studies
  - Effectiveness and completeness

Deriving Specific PS

- Domain prescriptions
  - Address: partial/total function
  - Boundary: e.g., upper/lower bounds
  - Type
    - expected) normal processing
    - unexpected: provide default values or perform exception handling
- Primitive invariants
  - Address: lack of intrinsic invariant
  - Relations based on physical law
  - Use TFM-based FTA and ETA to identify entities to check

- e.g., conservation law

$$\Delta P_i = P_i(t_1) - P_i(t_0) = G_i(t_0, t_1) - T_i(t_0, t_1)$$

Deriving Specific PS (II)

- Safety assertions
  - Address: physical/safety limits
  - Directly from physical/safety limits
  - Indirect assertions
    - related program variables
    - based on TFM-based FTA and ETA
- Image consistency assertions
  - Address: discrete vs. continuous
  - State or status checking
  - Rate checking

Deriving Specific PS (III)

- Entity dependency assertions
  - Address: linkage among components

    (discrete/continuous and semantic gap)

  - Functional/relational dependencies

  - Operational characteristics according to physical laws
- Temporal dependency assertions
  - Address: temporal relations among components

    (discrete/continuous and semantic gap)

  - Temporal relations/dependencies

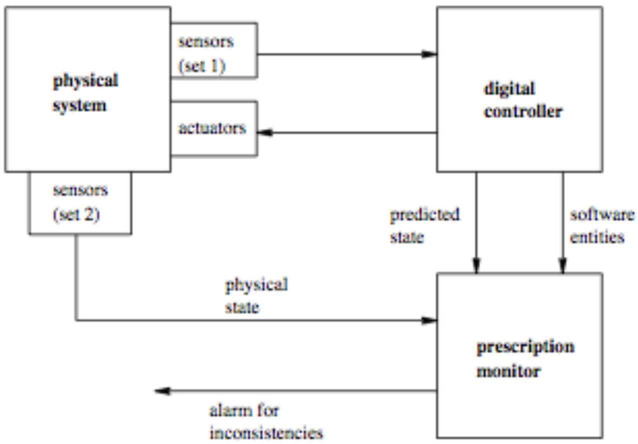
  - Time delay effect according to physical laws
  - CCSCS are real-time systems

A Comprehensive Case Study

- Selecting a case study
  - Several case studies performed
  - TMI-2: Three Mile Island accident
  - Simulator of TMI-2 accident
  - Seeding and detection of faults

- A simulator with components
    - digital controller (pseudo-program chart)
    - physical system with 4 process variables: power, temp, pressure, water level
    - introducing prescription monitor

Prescription Monitor in Case Study



- Prescription monitor: Fig 16.6 (p.281)
- Prescription monitor development
    - performance constraints
    - quality/reliability of itself?
    - usage of independent sets of sensors

Case Study (II)

- Developing PS in the case study
    - Generic assertions (domain etc.)
    - Specific assertions with examples
- Fault seeding: wide variety of faults
    - Erroneous input from the user (1-4)
    - Wrong data types or values (5-7)
    - Programming errors (8-16)
    - Wrong reading of sensors (17-19)
- Result: all detected by prescription monitor by specific PS

Case Study Summary

- Prescriptive specification checking

    - Based on TFM
    - Analyze system integrity weaknesses
    - Derive corresponding assertions or PS
    - Checking PS for hazard prevention
    - Appears to be effective in several case studies
- Future directions and development
    - Apply to realistic applications
    - Prescription monitor development
    - Support for PS derivation
    - Generalization to other systems
        - e.g., embedded systems
        - software-based heterogeneous systems...

Summary and Perspectives

- Software fault tolerance
    - Duplication and redundancy
    - Techniques: RB, NVP, and variations
    - Cost and effectiveness concerns
- SSE: Augment S/W Engineering
    - Analysis to identify hazard
    - Design for safety
    - Safety constraints and verification
    - Leveson's s/w safety program, PSC, etc.
    - Cost and application concerns
- Comparison to other QA: Chapter 17