Scalable Software Testing and Verification Through Heuristic Search and Optimization: Experiences and Lessons Learned

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Scalable Software Testing and Verification Through Heuristic Search and Optimization

Verification, Testing

- The term “verification” is used in its wider sense: Defect detection.
- Testing is, in practice, the most common verification technique.
- Testing is about systematically, and preferably automatically, exercise a system such as to maximize chances of uncovering (important) latent faults within time constraints.
- Other forms of verifications are important too (e.g., design time, run-time), but much less present in practice.
- Decades of research have not yet significantly and widely impacted software verification practice.

Scalable? Applicable?

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- *Scalable:* Can a technology be applied on large artifacts (e.g., models, data sets, input spaces) and still provide useful support within reasonable effort, CPU and memory resources?

- *Applicable:* Can a technology be efficiently and effectively applied by engineers in realistic conditions?
  - realistic ≠ universal

Metaheuristics

- *"A **metaheuristic** is a heuristic method for solving a very general class of computational problems by combining user given black-box procedures — usually heuristics themselves — in a hopefully efficient way." (Wikipedia)*

- Hill climbing, Tabu search, Simulated Annealing, Genetic algorithms, Ant colony optimisation ….

- Our research is agnostic to any specific technology but is driven by problems – the use of metaheuristics is however a recurring pattern. Why?

Talk Outline

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- Selected project examples, with industry collaborations
- Similarities and patterns
- Lessons learned

Testing Software Controllers

References:

- *R. Matinnejad et al., "Effective Test Suites for Mixed Discrete-Continuous Stateflow Controllers", ACM ESEC/FSE 2015*
- *R. Matinnejad et al., "MiL Testing of Highly Configurable Continuous Controllers: Scalable Search Using Surrogate Models", IEEE/ACM ASE 2014*
- *R. Matinnejad et al., "Search-Based Automated Testing of Continuous Controllers: Framework, Tool Support, and Case Studies", Information and Software Technology, Elsevier (2014)*

Electronic Control Units (ECUs)

Comfort and variety

More functions

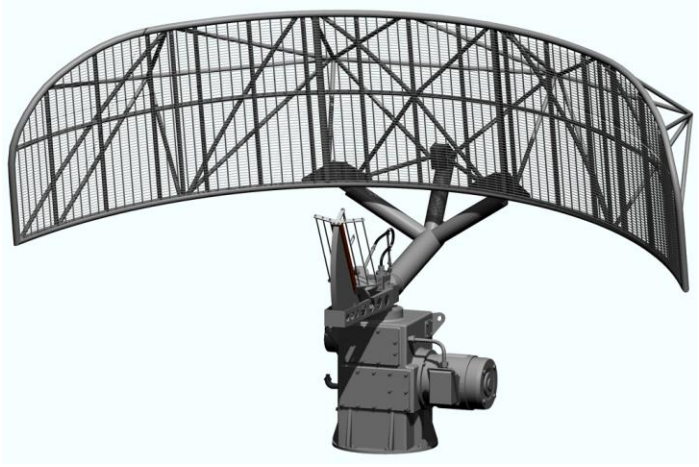
Safety and reliability

Faster time-to-market

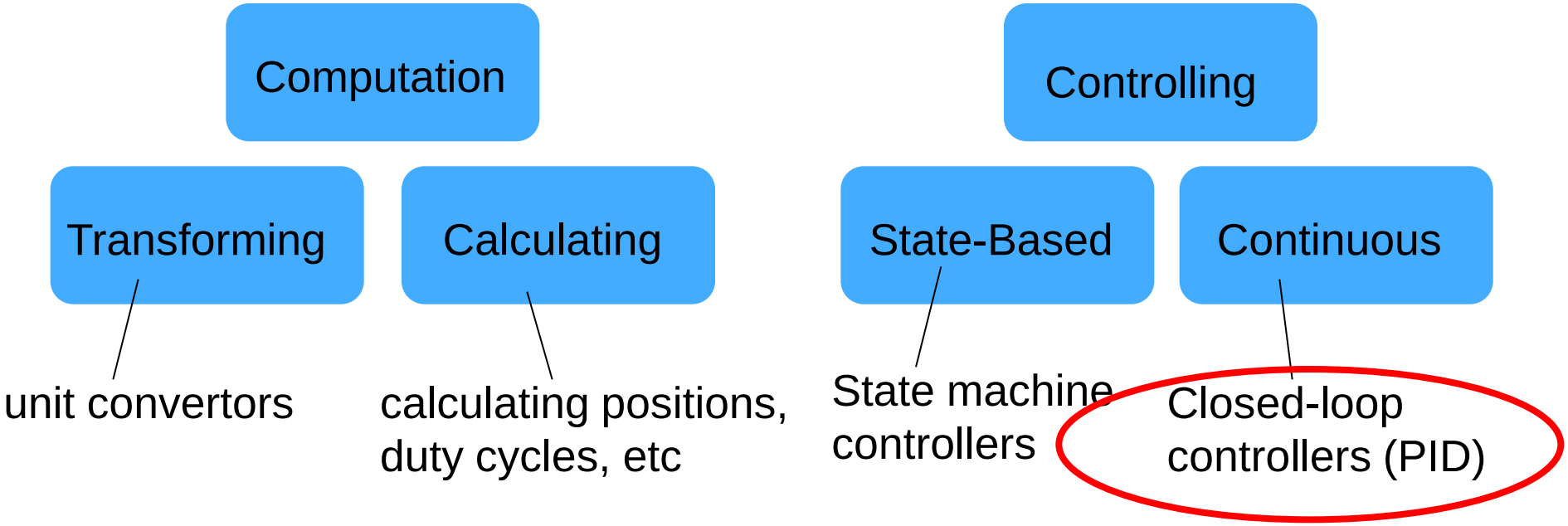
Greenhouse gas emission laws

Less fuel consumption

Dynamic Continuous Controllers



A Taxonomy of Automotive Functions



Different testing strategies are required for different types of functions

Development Process

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Model-in-the-Loop Stage

Simulink Modeling

MiL Testing

Generic Functional Model

Software-in-the-Loop Stage

Code Generation and Integration

SiL Testing

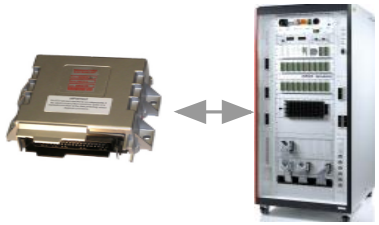
program

Software Release

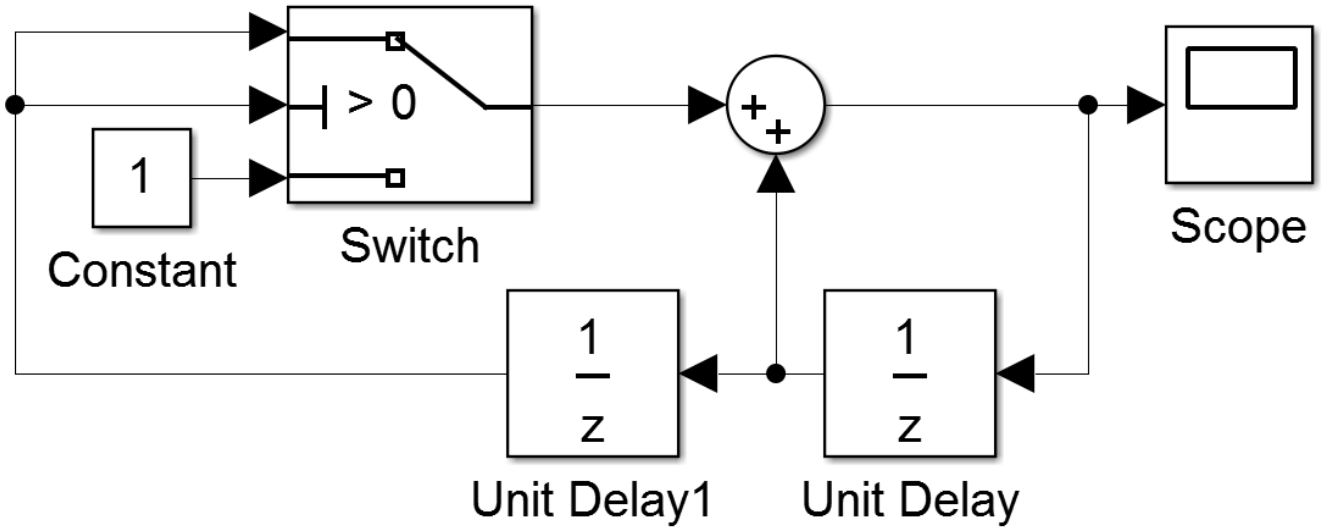
Hardware-in-the-Loop Stage

Software Running on ECU

HiL Testing

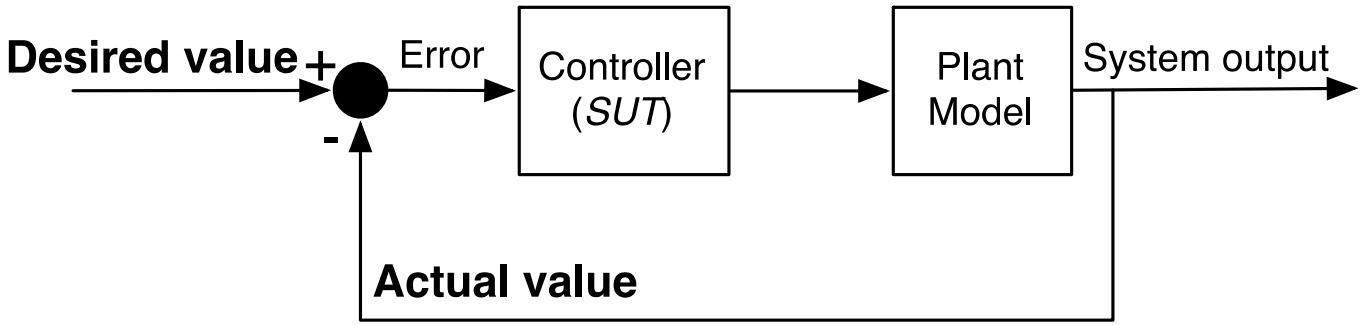


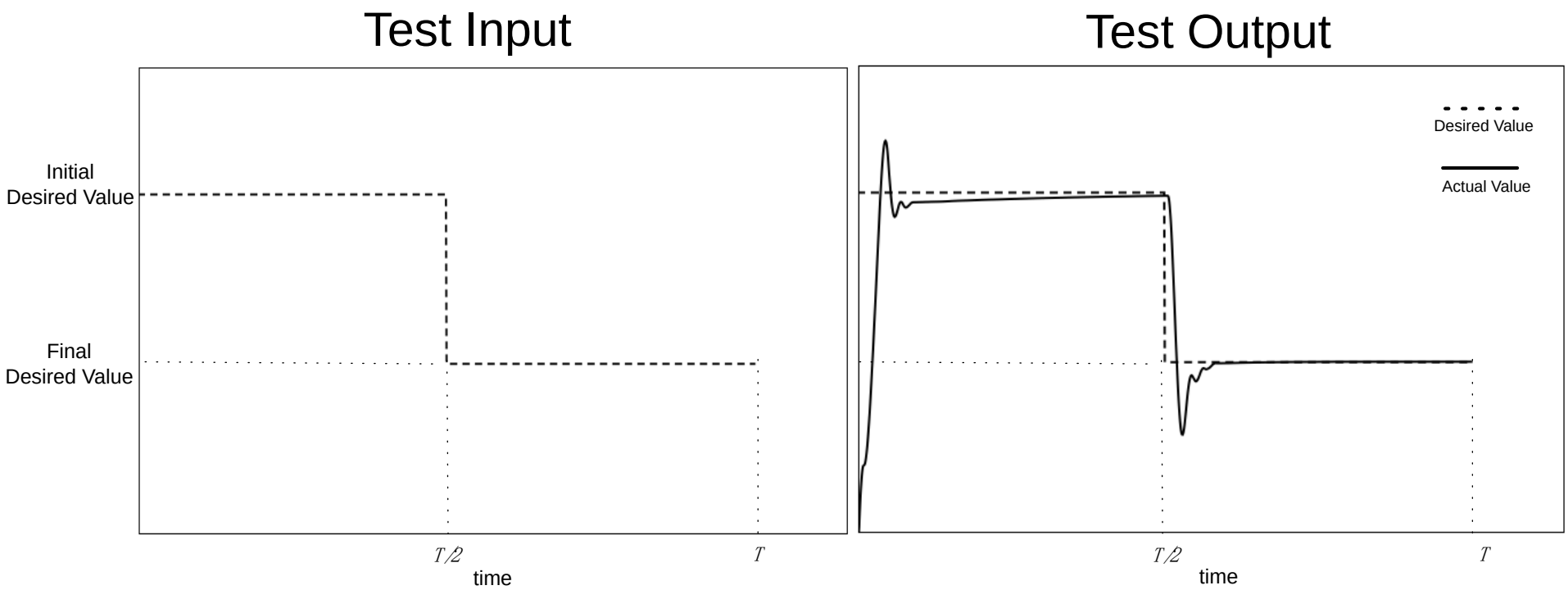
MATLAB/Simulink model



Fibonacci sequence: 1,1,2,3,5,8,13,21,…

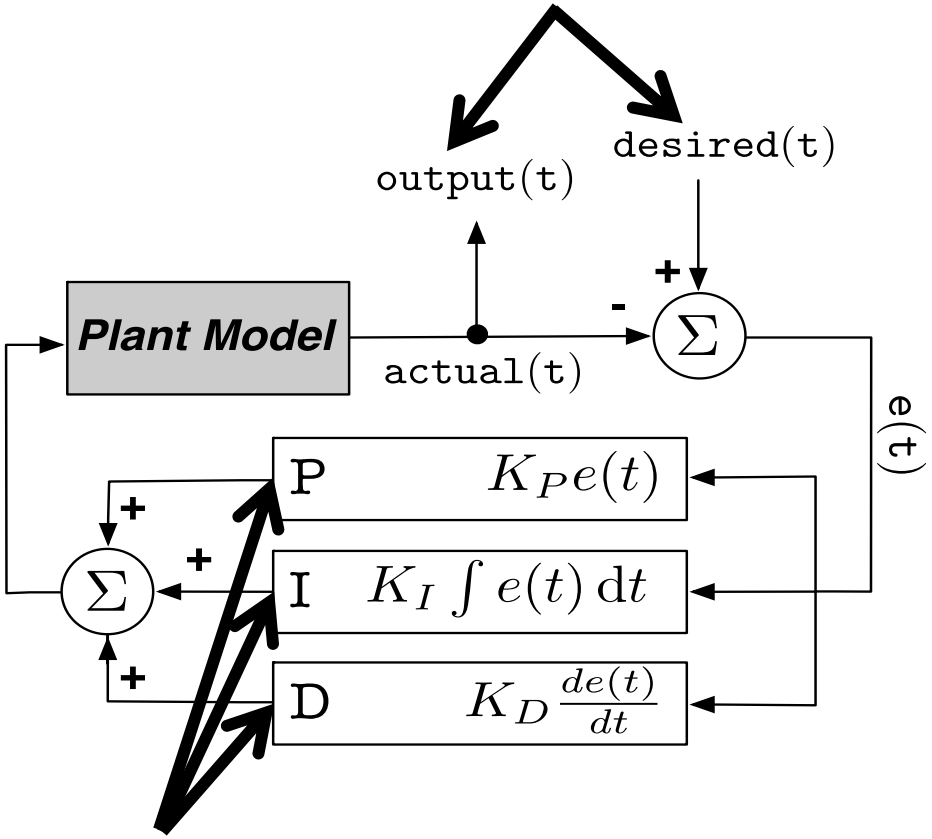
Controller Input and Output at MIL





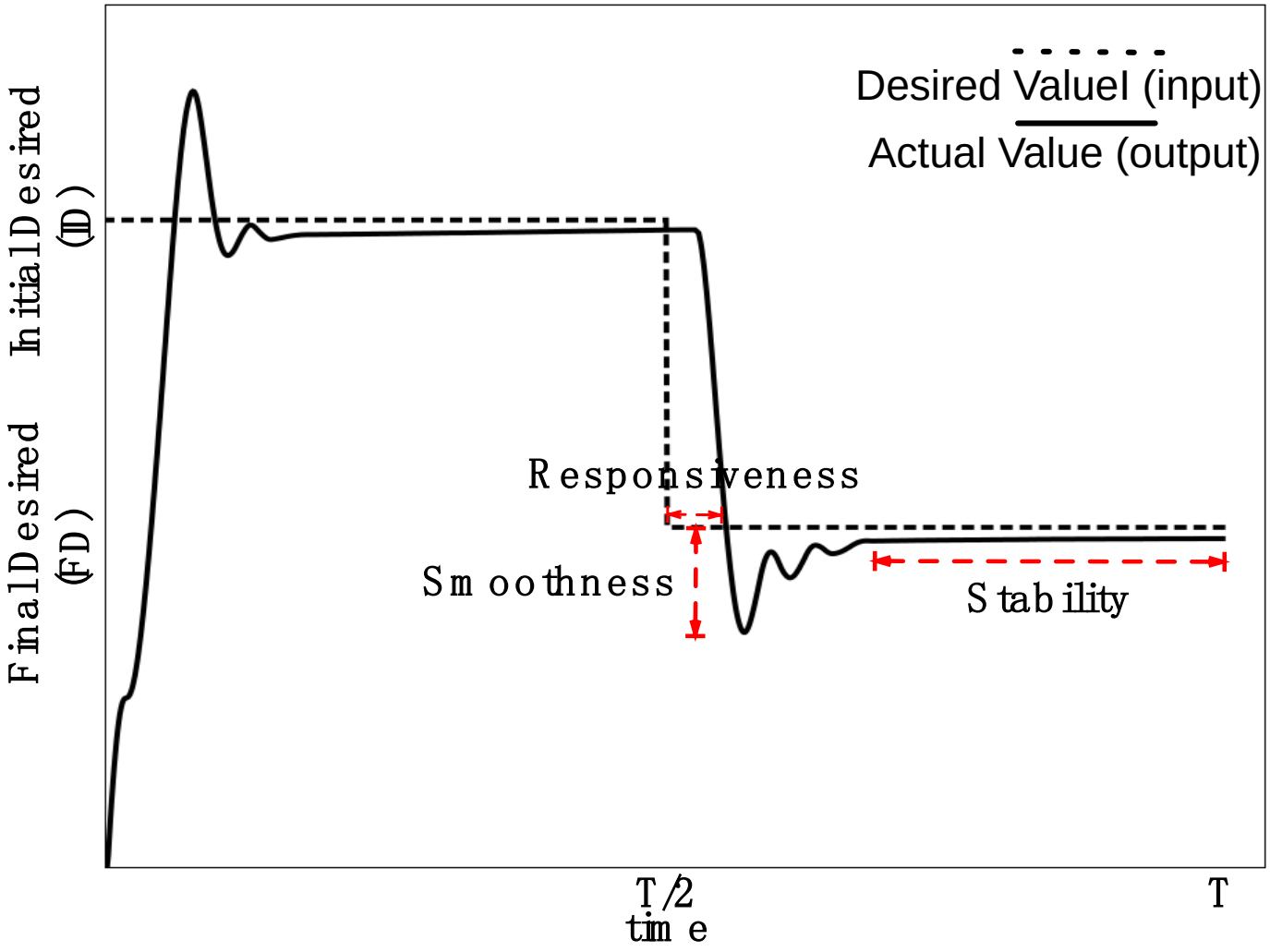
Controllers at MIL

Inputs: Time-dependent variables

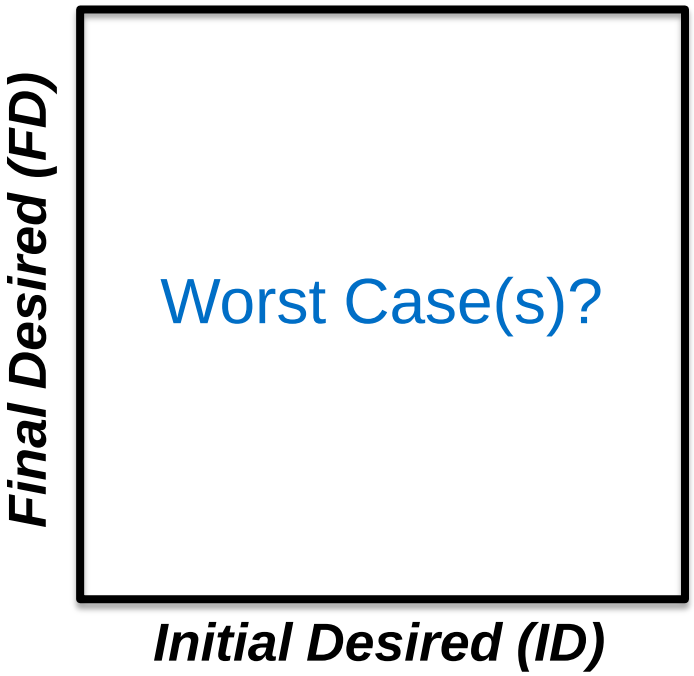


Configuration Parameters

Requirements and Test Objectives

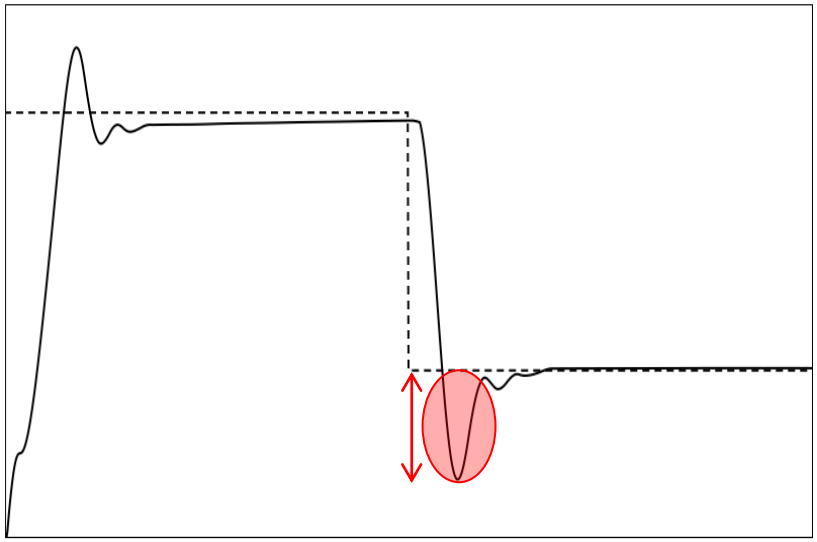


Test Strategy: A Search-Based Approach

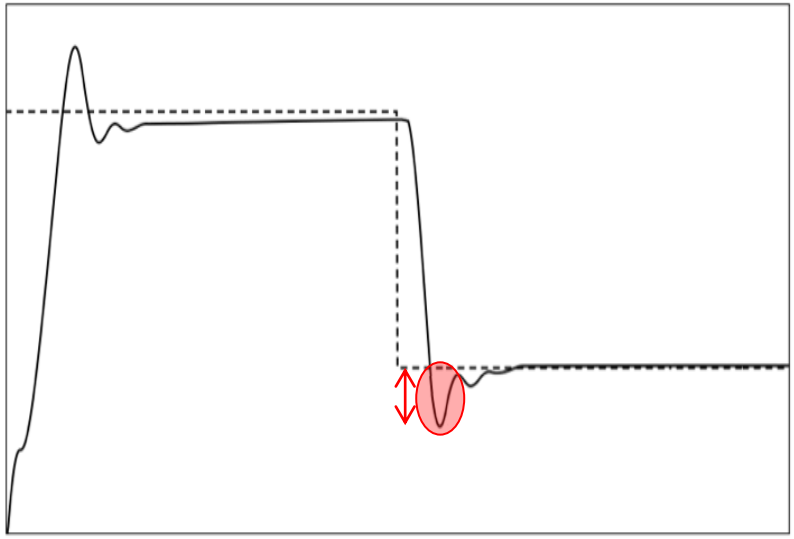


- Continuous behavior
- Controller's behavior can be complex
- Meta-heuristic search in (large) input space: Finding worst case inputs
- Possible because of automated oracle (feedback loop)
- Different worst cases for different requirements
- Worst cases may or may not violate requirements

Smoothness Objective Functions: $O_{Smoothness}$



Test Case A



Test Case B

$O_{Smoothness}$(Test Case A) **>** $O_{Smoothness}$(Test Case B)

We want to find test scenarios which maximize $O_{Smoothness}$

Search Elements

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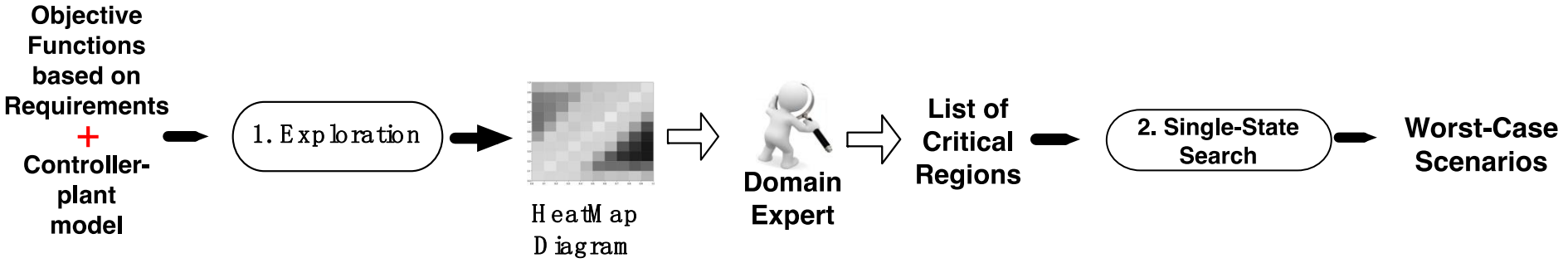
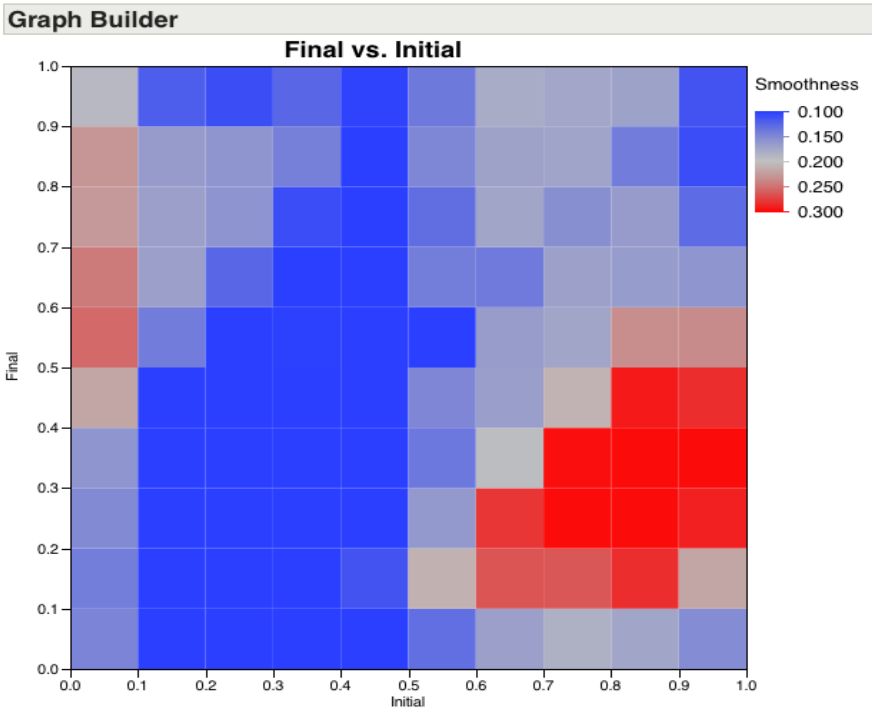
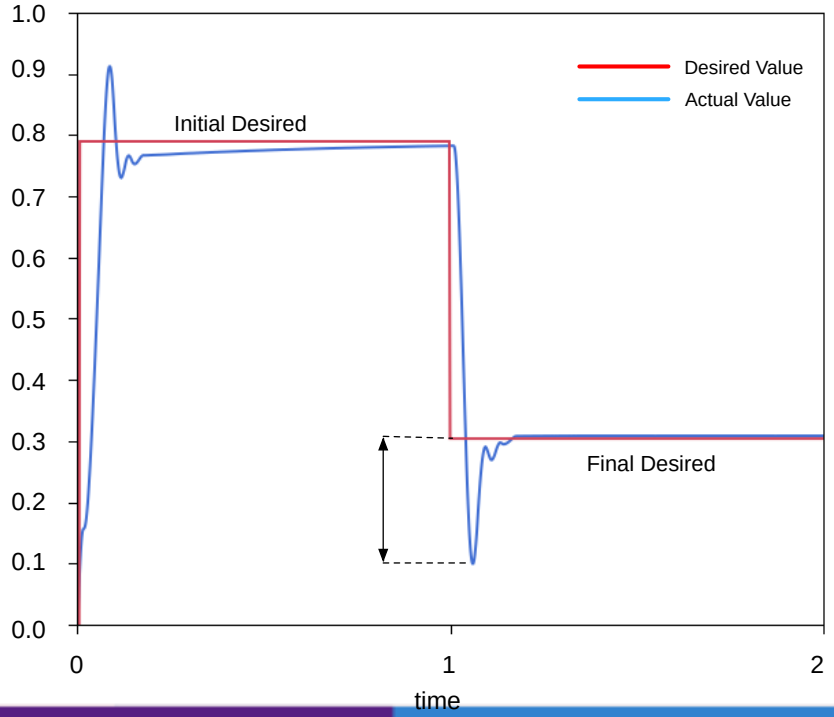
- **Search Space:**
  - Initial and desired values, configuration parameters
- **Search Technique:**
  - (1+1) EA, variants of hill climbing, GAs …
- **Search Objective:**
  - Objective/fitness function for each requirement
- **Evaluation of Solutions**
  - Simulation of Simulink model => fitness computation
- **Result:**
  - Worst case scenarios or values to the input variables that (are more likely to) break the requirement at MiL level
  - Stress test cases based on actual hardware (HiL)

Solution Overview (Simplified Version)

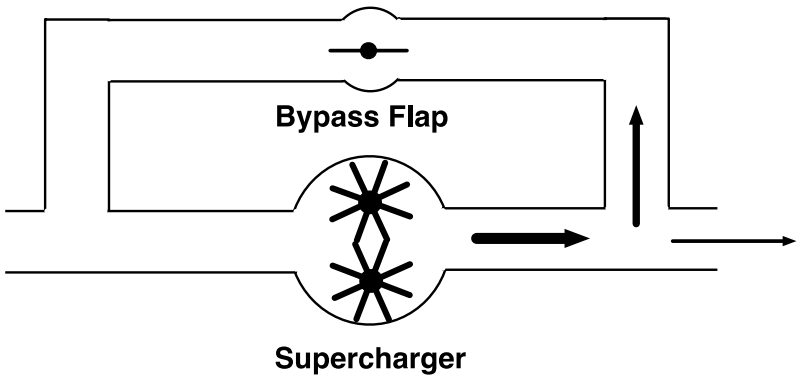




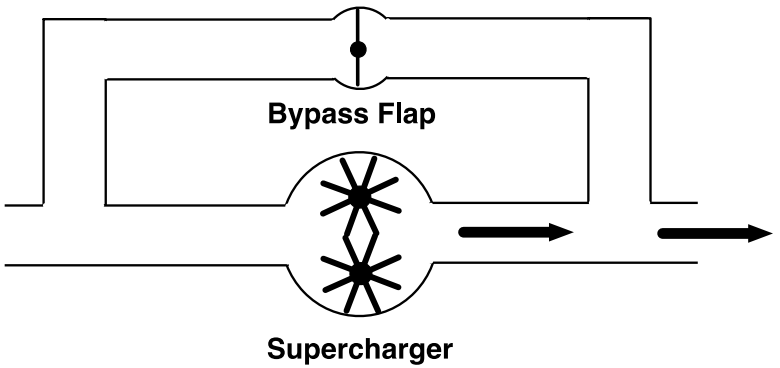


Automotive Example

- **Supercharger bypass flap controller**
  - ✓Flap position is bounded within [0..1]
  - ✓Implemented in MATLAB/Simulink
  - ✓34 sub-components decomposed into 6 abstraction levels
  - ✓The simulation time T=2 seconds

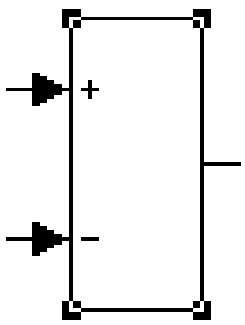


Flap position = 0 (open)

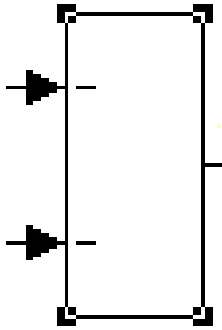


Flap position = 1 (closed)

Finding Seeded Faults



Inject Fault



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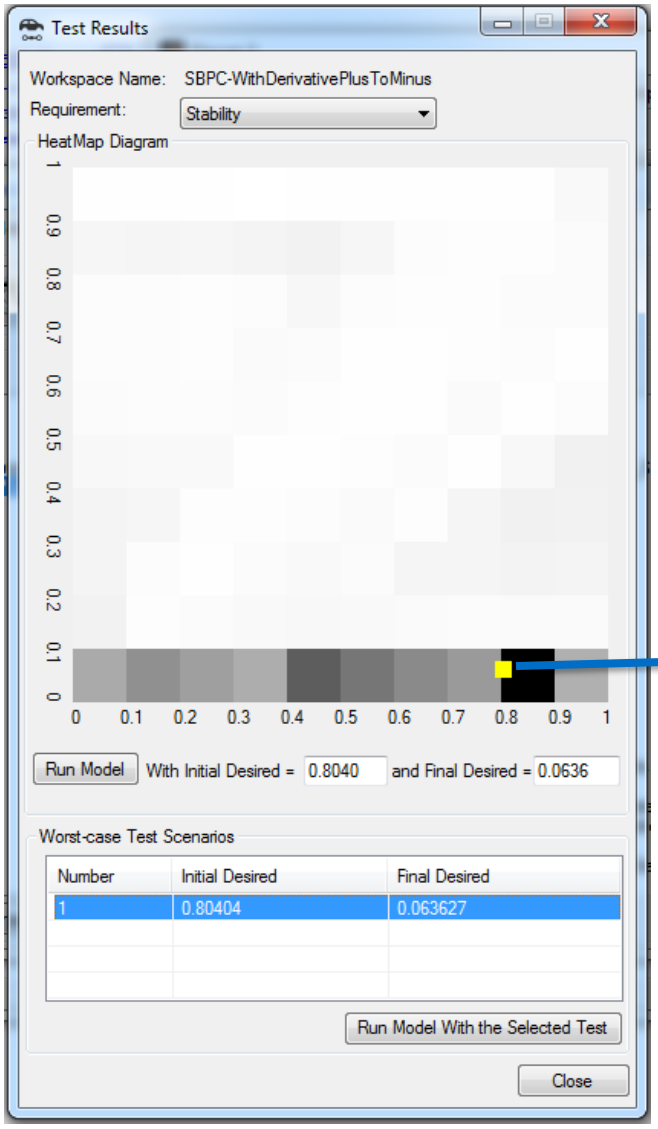
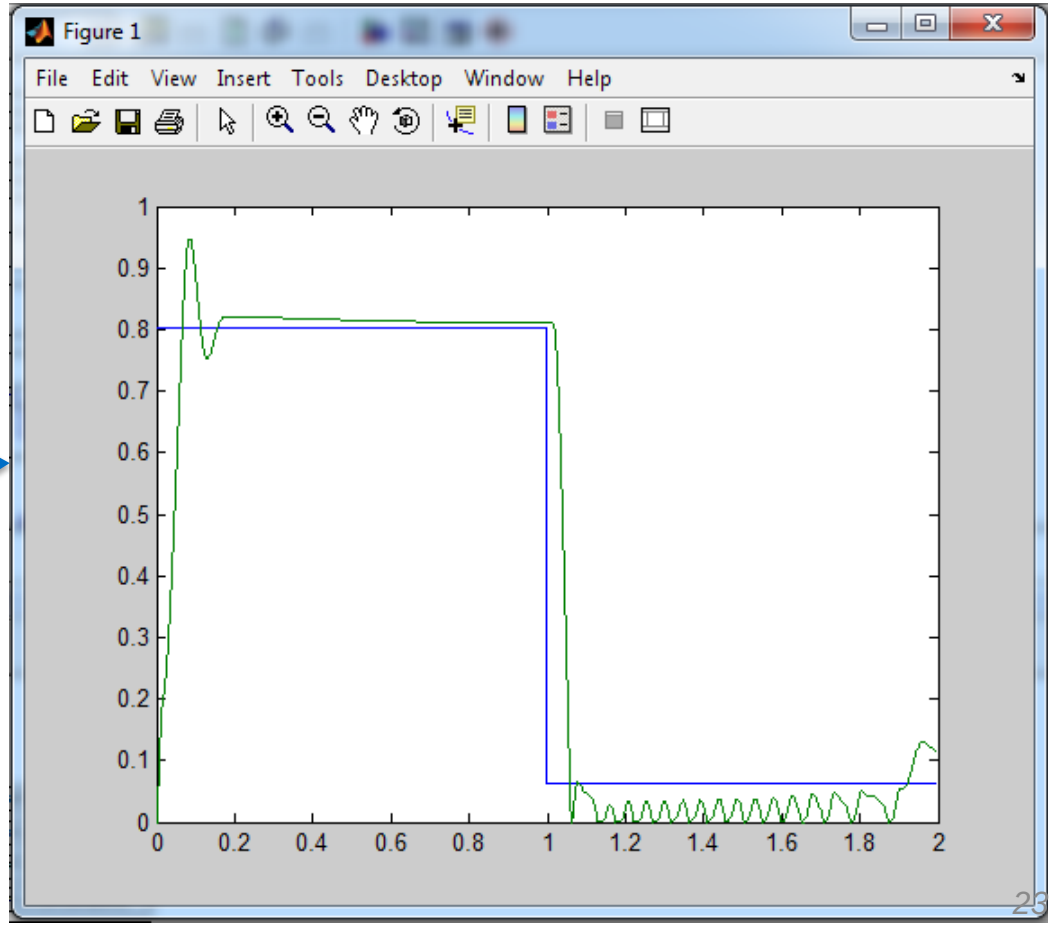
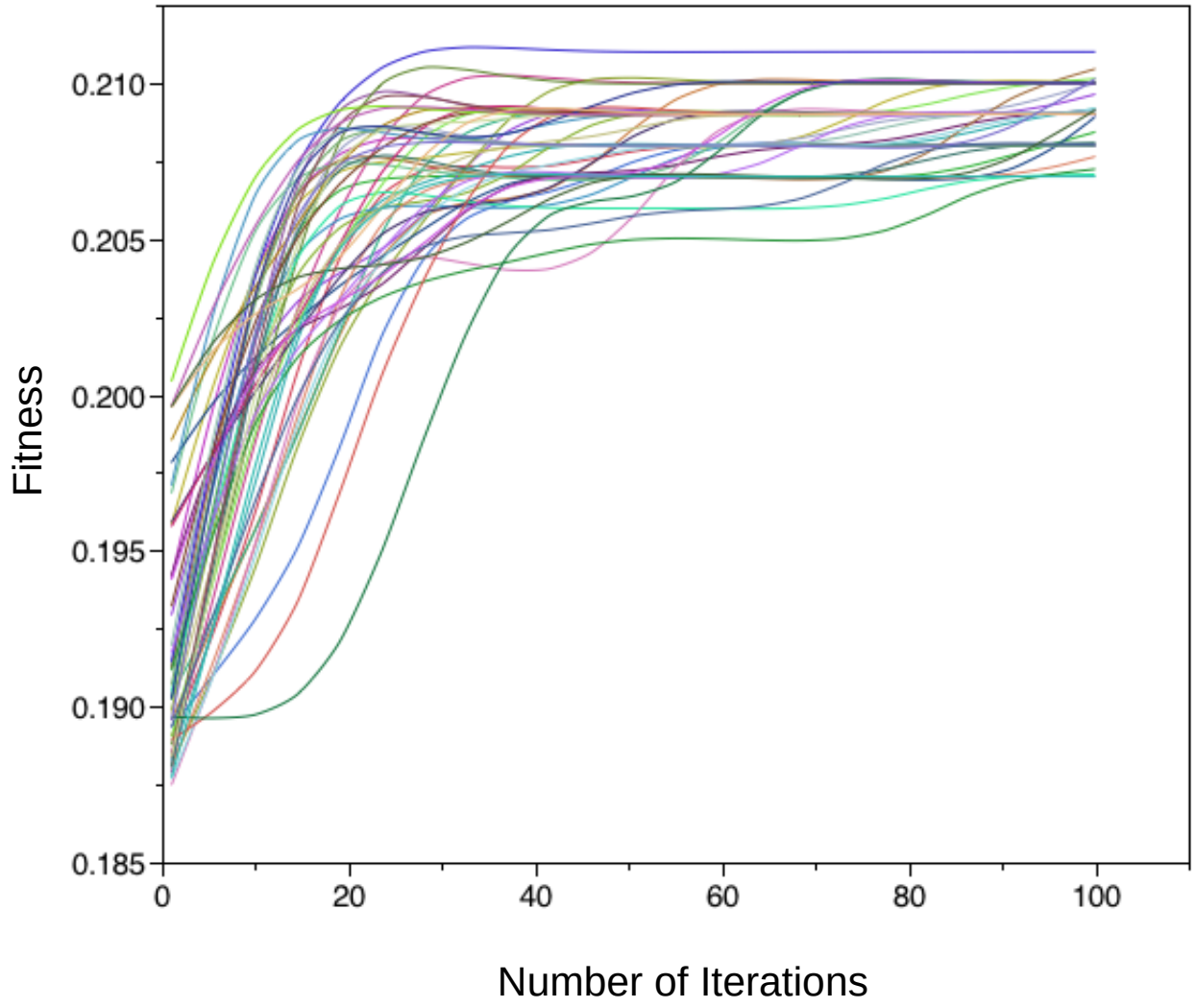
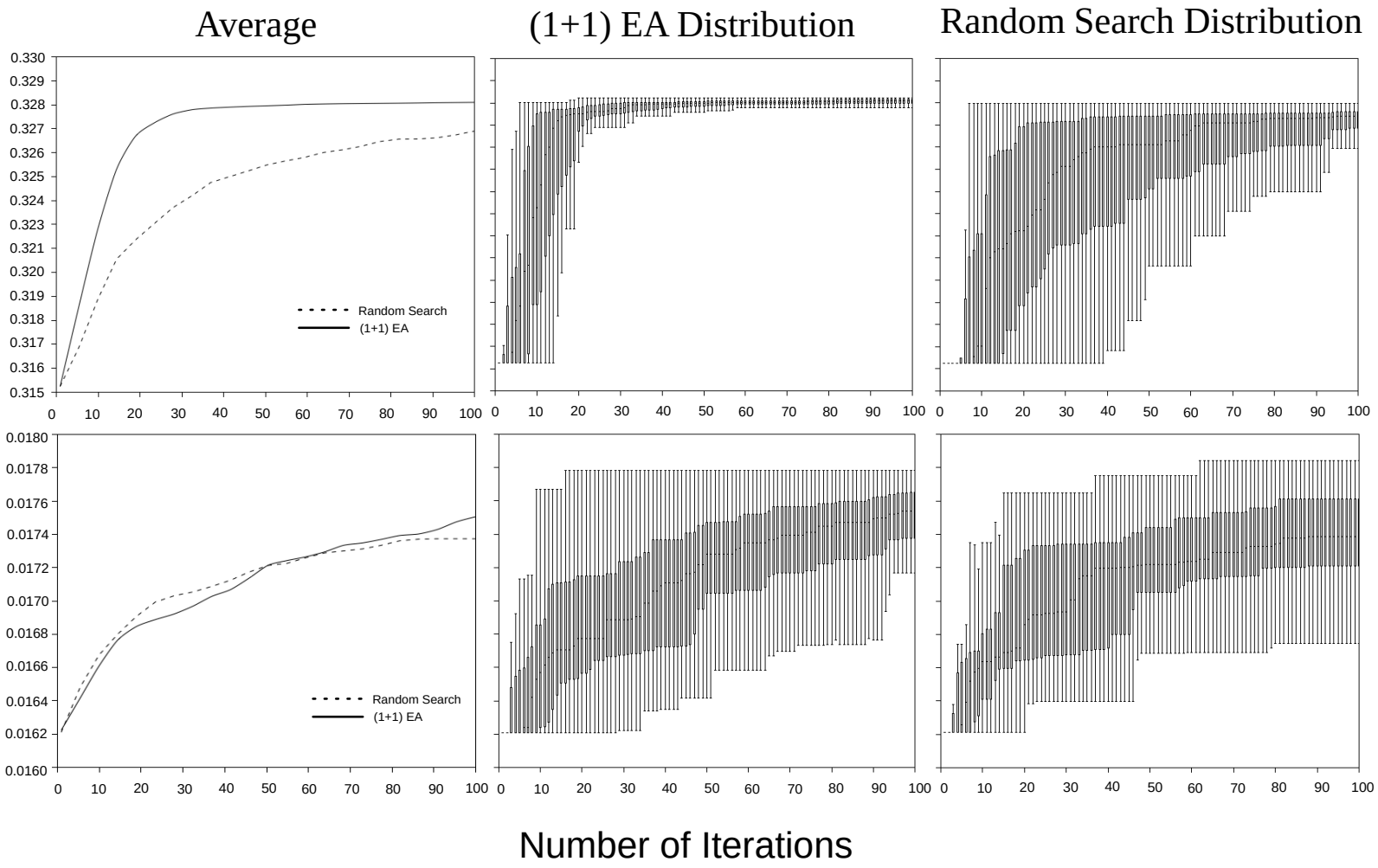




Analysis – Fitness increase over iterations

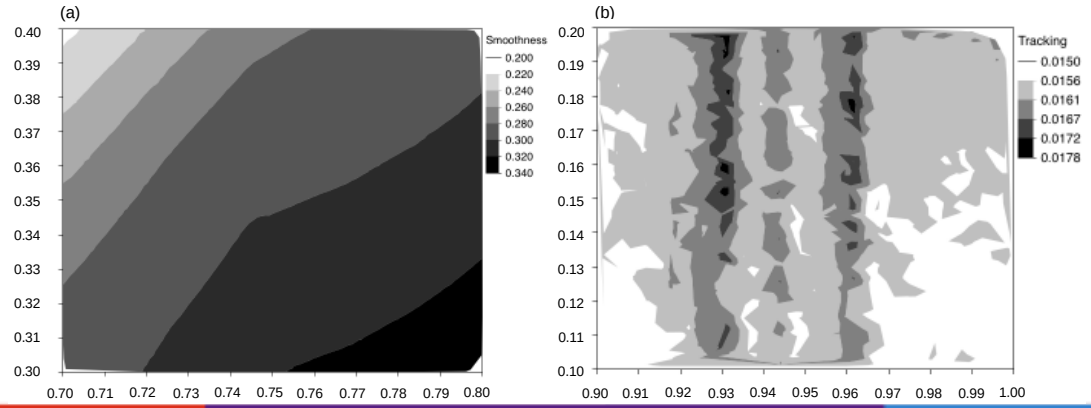


Analysis II – Search over different regions



Conclusions

- We found much worse scenarios during MiL testing than our partner had found so far, and much worse than random search (baseline)
- These scenarios are also run at the HiL level, where testing is much more expensive: MiL results -> test selection for HiL
- But further research was needed:
  - Simulations are expensive
  - Configuration parameters
  - Dynamically adjust search algorithms in different subregions (exploratory <-> exploitative)



Testing in the Configuration Space

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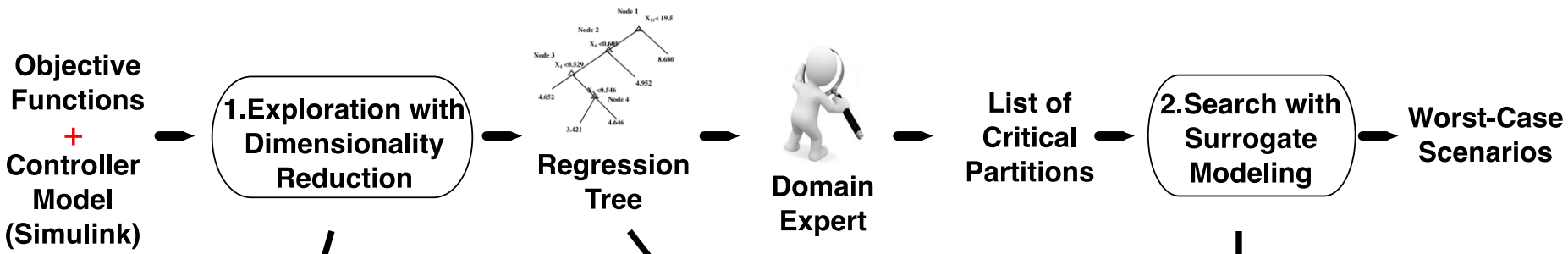
- MIL testing for all feasible configurations
- The search space is much larger
- The search is much slower (Simulations of Simulink models are expensive)
- Results are harder to visualize
- Not all configuration parameters matter for all objective functions

Modified Process and Technology

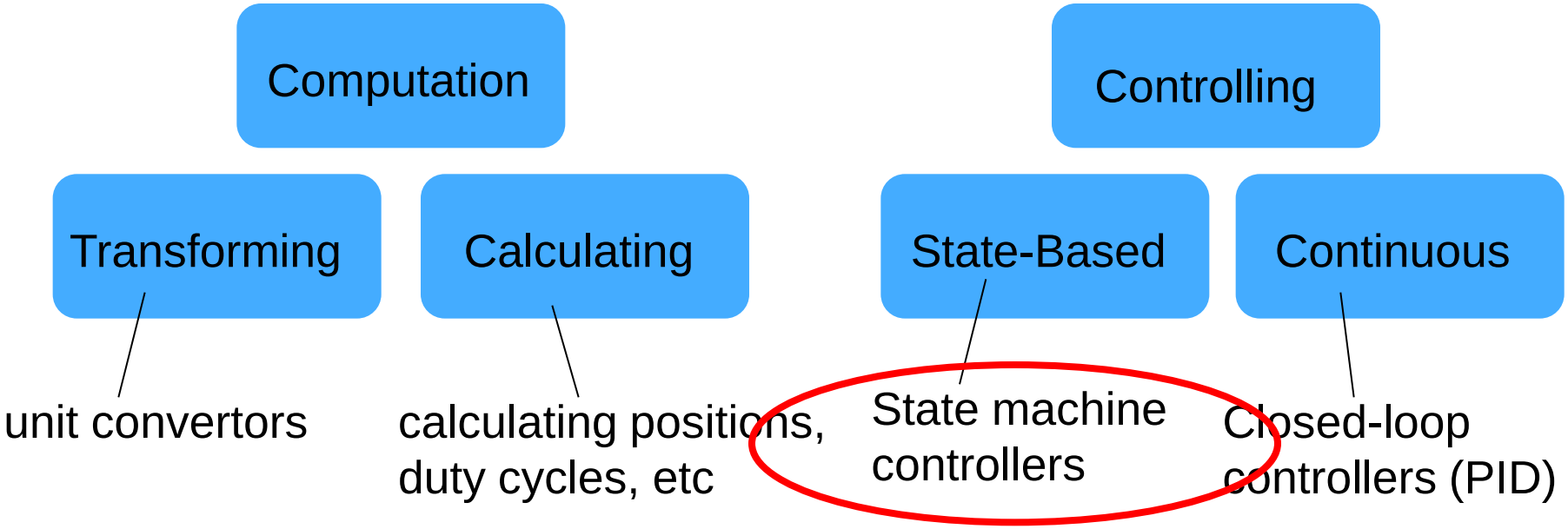


Dimensionality reduction to identify the significant variables

Visualization of the 8-dimension space using regression trees

Surrogate modeling to predict the objective function and speed up the search

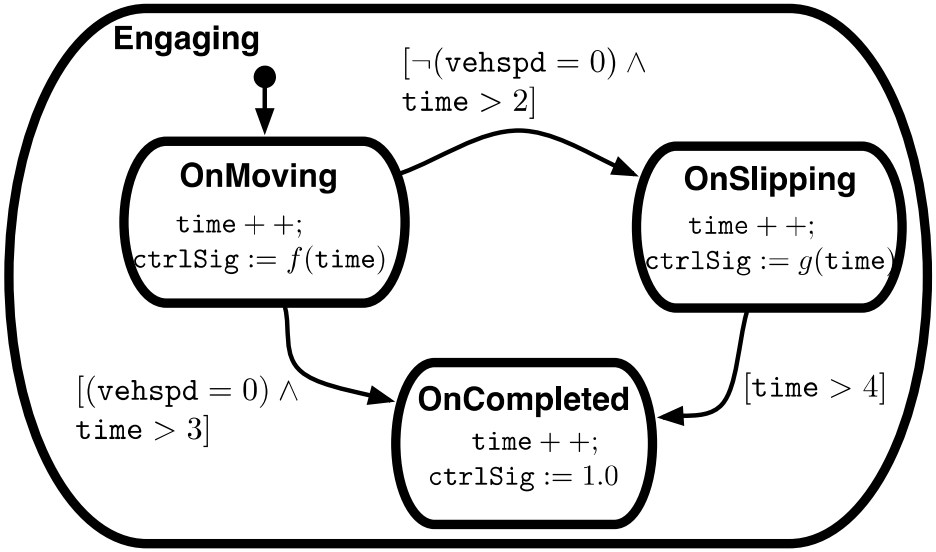
A Taxonomy of Automotive Functions



Different testing strategies are required for different types of functions

Differences with Close-Loop Controllers

- Mixed discrete-continuous behavior: Simulink stateflows
- Much quicker simulation time
- No feedback loop -> no automated oracle
- The main testing cost is the manual analysis of output signals
- Goal: Minimize test suites
- Challenge: Test selection
- Entirely different approach to testing



Selection Strategies

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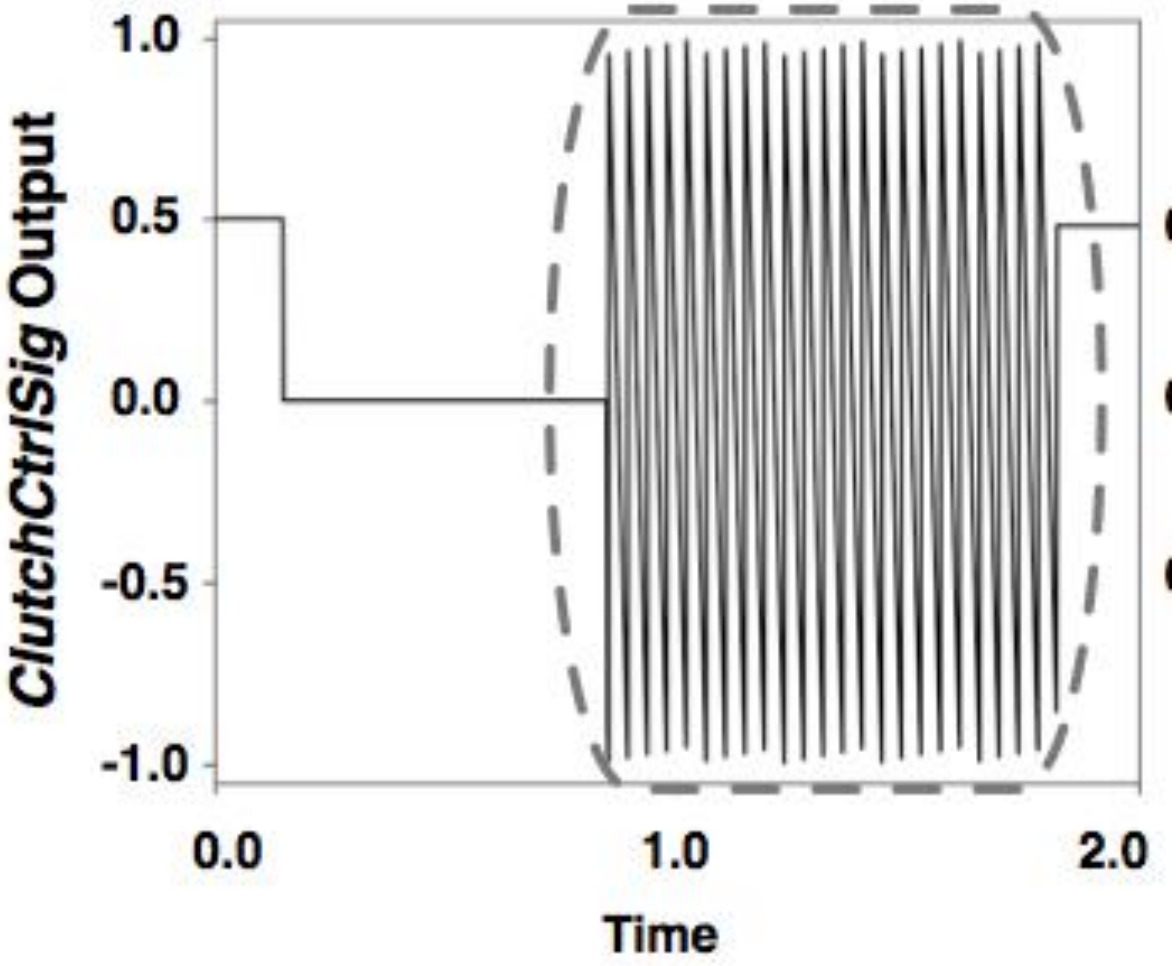
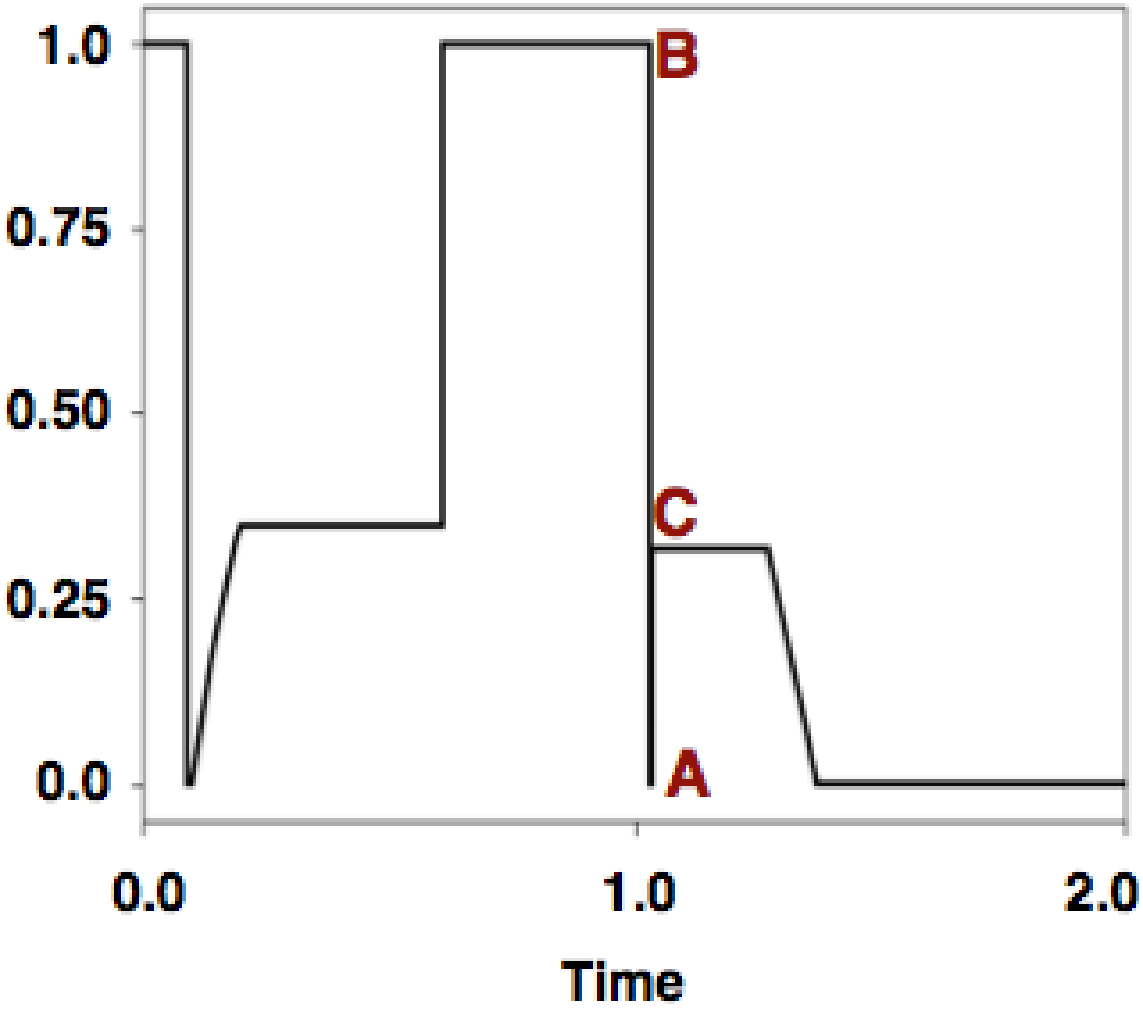
- Adaptive Random Selection
- White-box Structural Coverage
  - State Coverage
  - Transition Coverage
- Output Diversity
- Failure-Based Selection Criteria (search)
  - Domain specific failure patterns
  - Output Stability
  - Output Continuity

Stability



Continuity



Minimizing CPU Shortage Risks During Integration

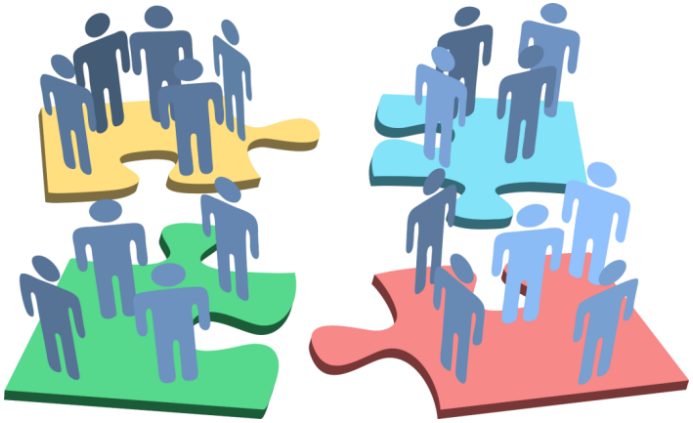
References:

- *S. Nejati et al., "Minimizing CPU Time Shortage Risks in Integrated Embedded Software", in 28th IEEE/ACM International Conference on Automated Software Engineering (ASE 2013), 2013*
- *S. Nejati, L. Briand, "Identifying Optimal Trade-Offs between CPU Time Usage and Temporal Constraints Using Search", ACM International Symposium on Software Testing and Analysis (ISSTA 2014), 2014*

Automotive: Distributed Development

Software Integration

Stakeholders



Car Makers

- Develop software optimized for their specific hardware
- Provide part suppliers with runnables (exe)

Part Suppliers

- Integrate car makers software with their own platform
- Deploy final software on ECUs and send them to car makers

Different Objectives

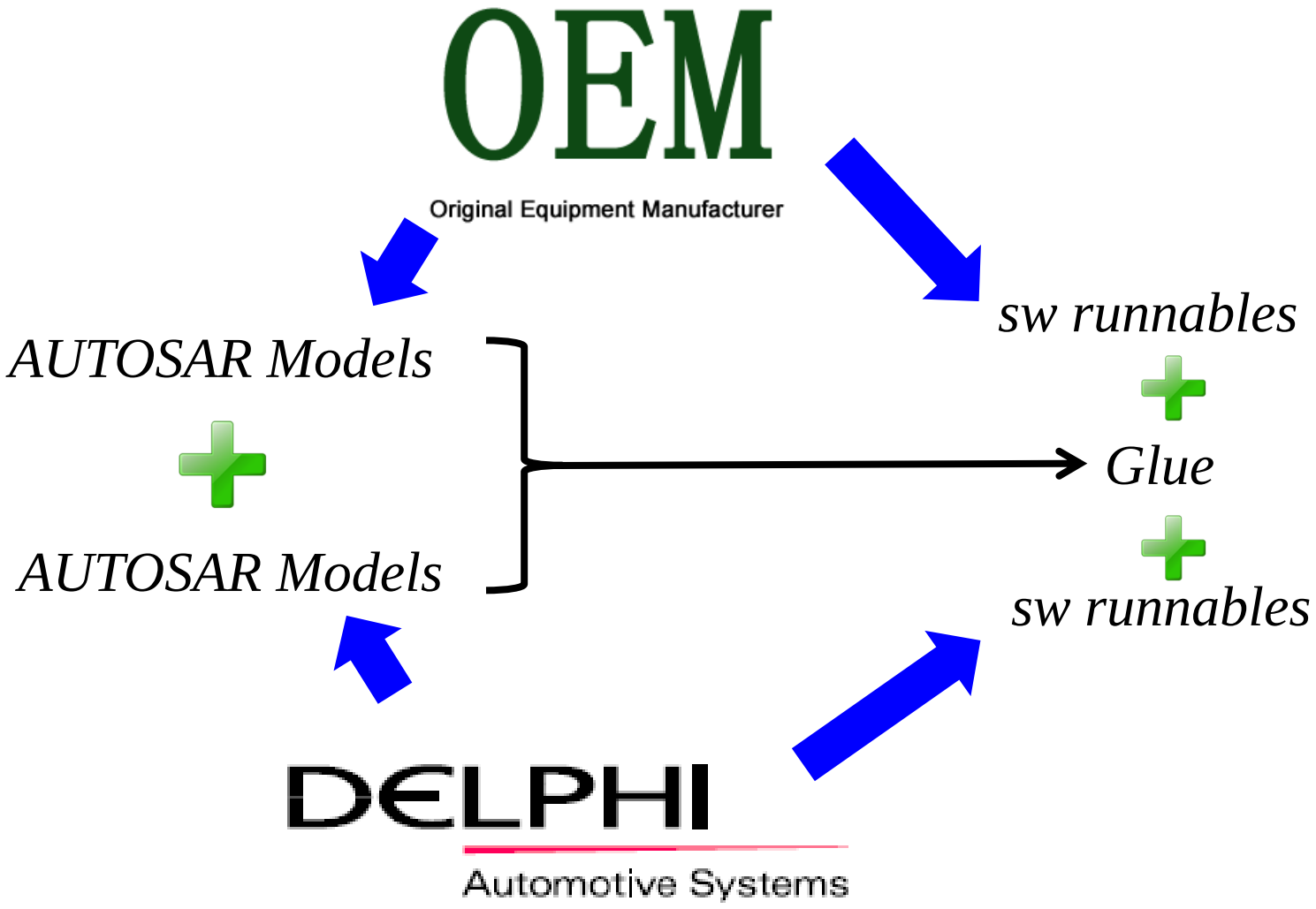
Car Makers

- Objective: Effective execution and synchronization of runnables
- Some runnables should execute simultaneously or in a certain order

Part Suppliers

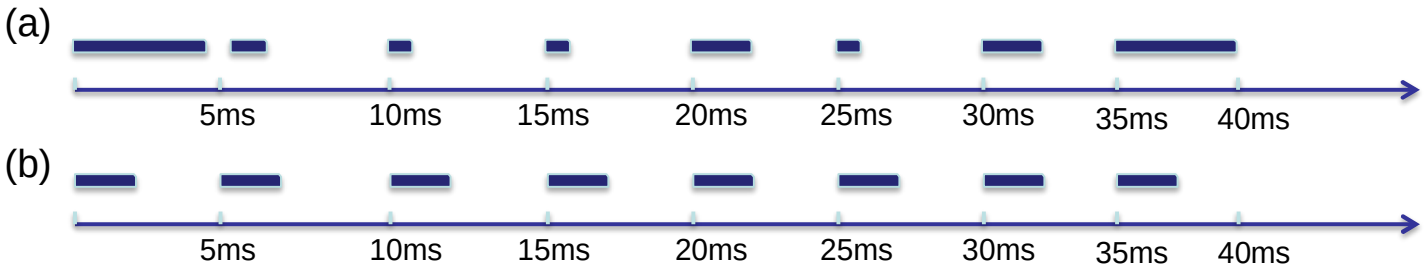
- Objective: Effective usage of CPU time
- Max CPU time used by all the runnables should remain as low as possible over time

An overview of an integration process in the automotive domain

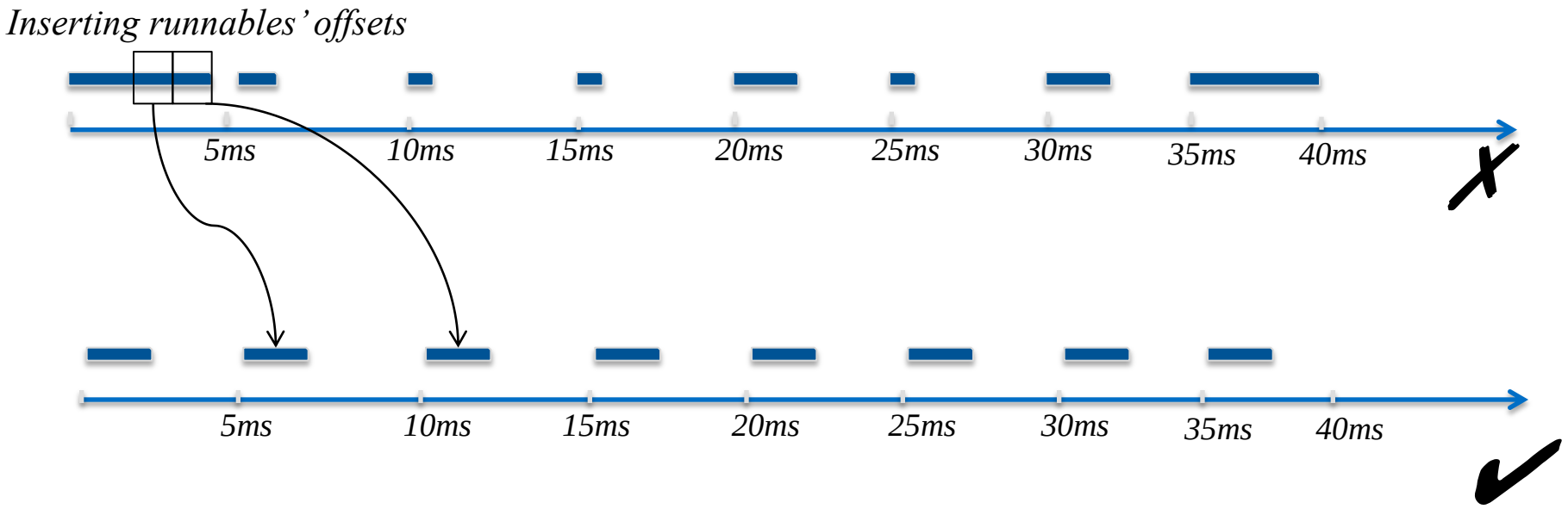


CPU time shortage

- Static cyclic scheduling: predictable, analyzable
- Challenge
  - Many OS tasks and their many runnables run within a limited available CPU time
    - The execution time of the runnables may exceed their time slot
- Our goal
  - Reducing the maximum CPU time used per time slot to be able to
    - Minimize the hardware cost
    - Reduce the probability of overloading the CPU in practice
    - Enable addition of new functions incrementally



Using runnable offsets (delay times)



Offsets have to be chosen such that

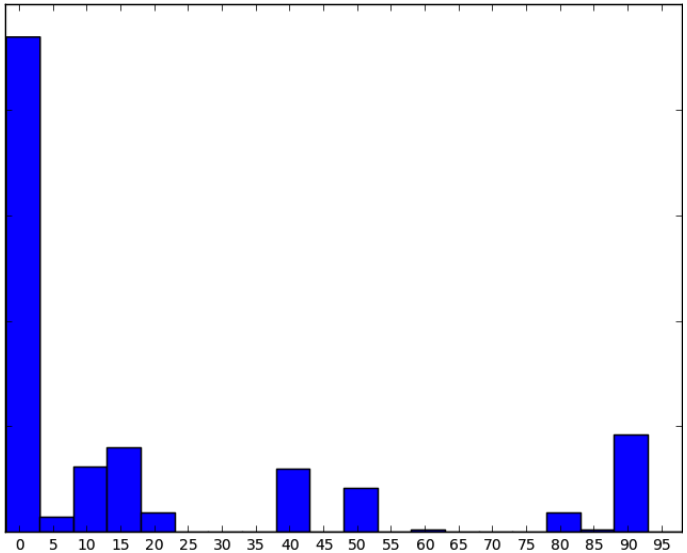
- the maximum CPU usage per time slot is minimized, and further,
  - the runnables respect their period
  - the runnables respect their time slot
  - the runnables satisfy their synchronization constraints

Search algorithms

- The objective function is the max CPU usage of a 2s-simulation of runnables
- The search modifies one offset at a time, and updates other offsets only if timing constraints are violated
- Single-state search algorithms for discrete spaces (HC, Tabu)

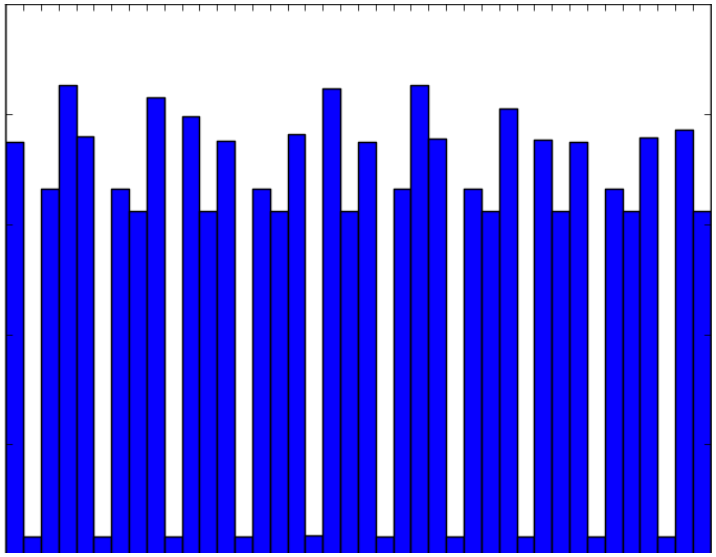
Case Study: an automotive software system with 430 runnables, search space = 10^27

5.34 ms



Running the system without offsets

2.13 ms



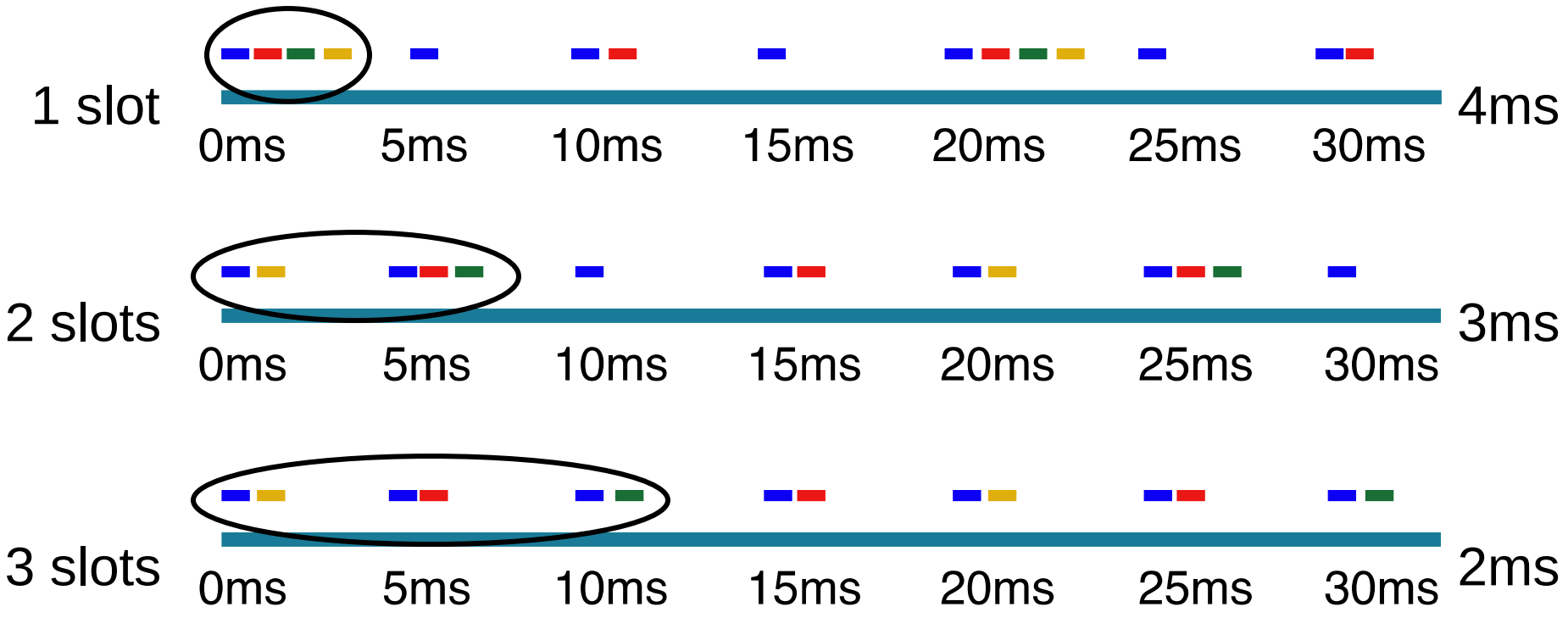
Optimized offset assignment

Trade-off between Objectives

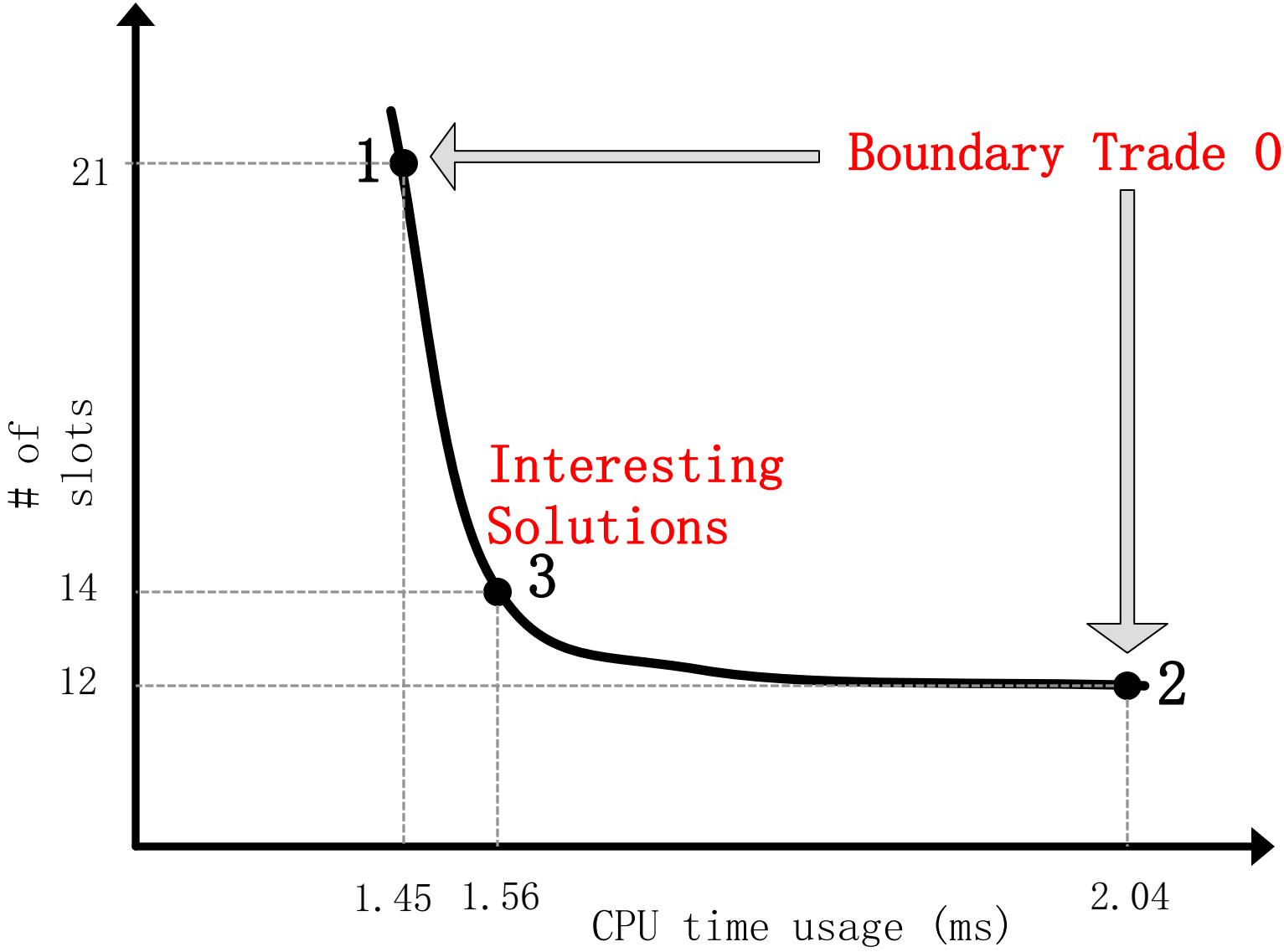
Car Makers r_0 r_1 r_2 r_3 **Part Suppliers**

Execute r_0 to r_3 close to one another.

Minimize CPU time usage



Trade-off curve

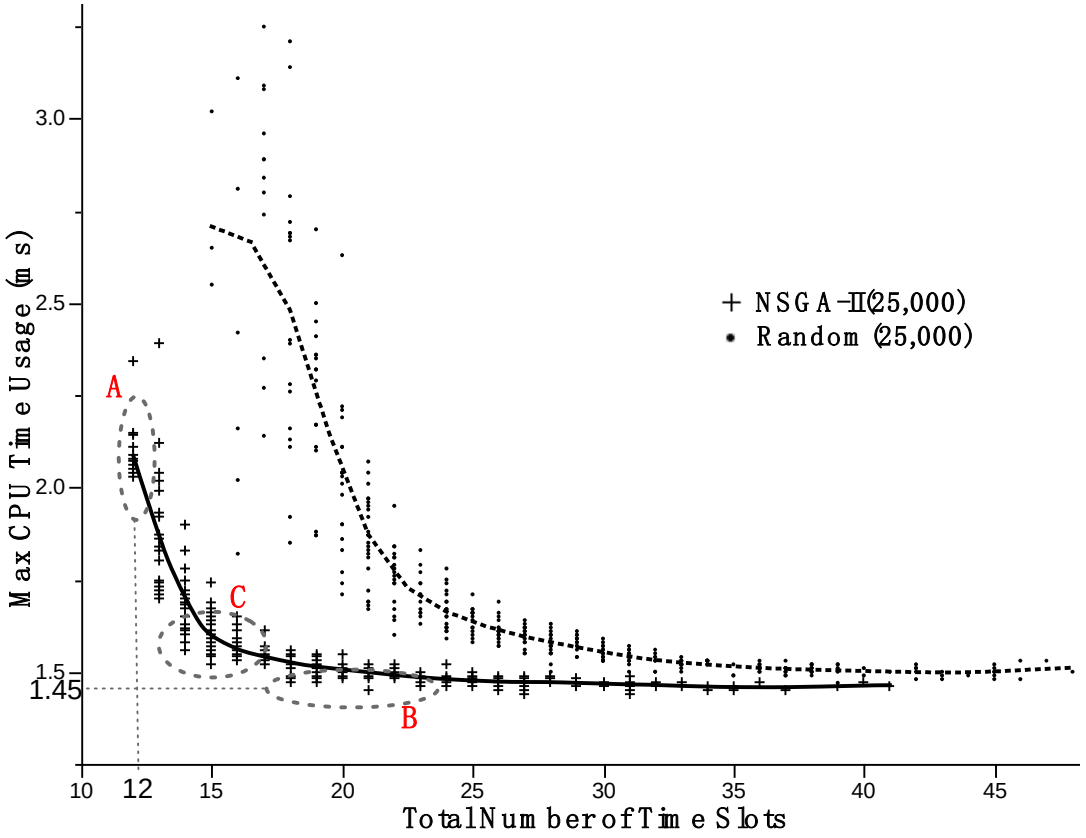


Multi-objective search

- Multi-objective genetic algorithms (NSGA II)
- Supporting decision making and negotiation between stakeholders

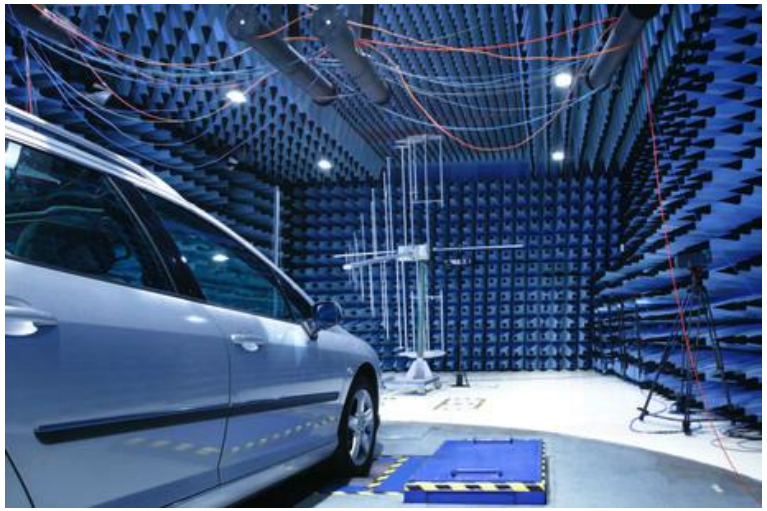
Objectives:

- (1) Max CPU time
- (2) Maximum time slots between “dependent” tasks



Conclusions

- Search algorithms to compute offset values that reduce the max CPU time needed
- Generate reasonably good results for a large automotive system and in a small amount of time
- Used multi-objective search → tool for establishing trade-off between relaxing synchronization constraints and maximum CPU time usage



Schedulability Analysis and Stress Testing

References:

- *S. Di Alesio et al., "Stress Testing of Task Deadlines: A Constraint Programming Approach", IEEE ISSRE 2013, San Jose, USA*
- *S. Di Alesio et al., "Worst-Case Scheduling of Software Tasks – A Constraint Optimization Model to Support Performance Testing, Constraint Programming (CP), 2014*
- *S. Di Alesio er al. "Combining Genetic Algorithms and Constraint Programming to Support Stress Testing", ACM TOSEM (forthcoming)*

Problem

- Schedulability analysis encompasses techniques that try to predict whether all (critical) tasks are schedulable, i.e., meet their deadlines
- Stress testing runs carefully selected test cases that have a high probability of leading to deadline misses
- Stress testing is complementary to schedulability analysis
- Testing is typically expensive, e.g., hardware in the loop
- Finding stress test cases is difficult

Finding Stress Test Cases is Difficult

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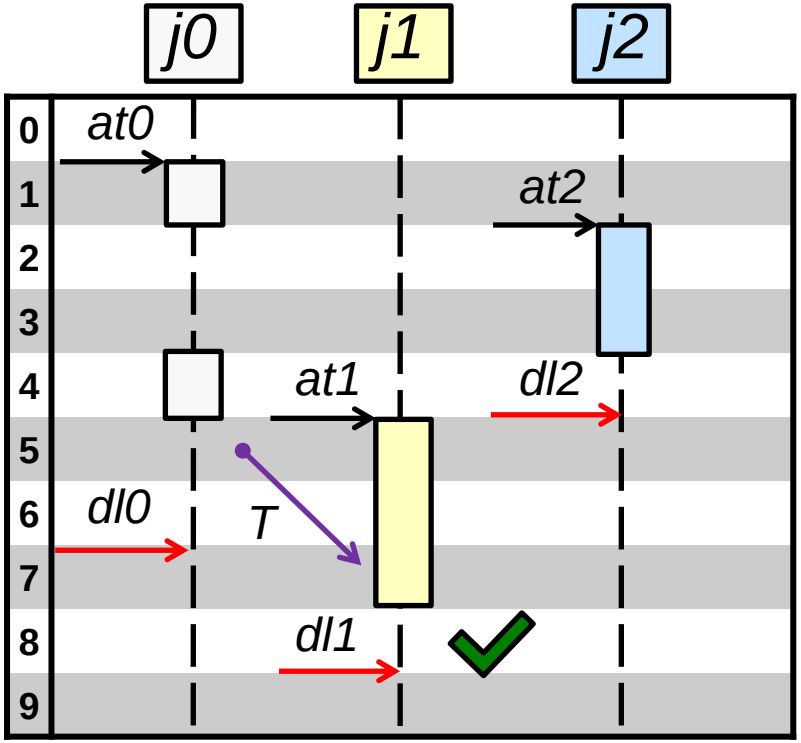
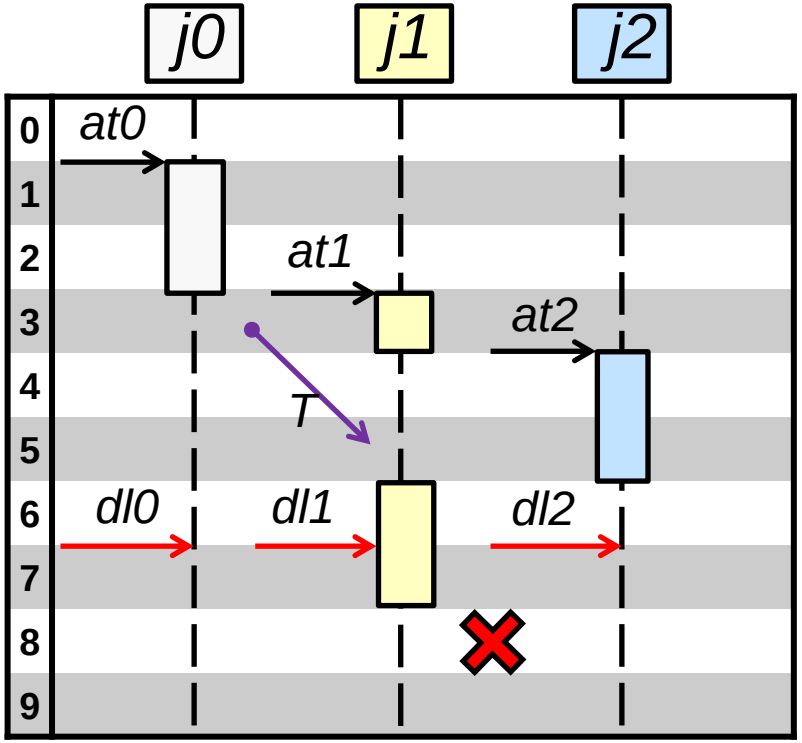
j0, j1 , j2 arrive at at0 , at1 , at2 and must finish before dl0 , dl1 , dl2





J1 can miss its deadline dl1 depending on when at2 occurs!

Challenges and Solutions

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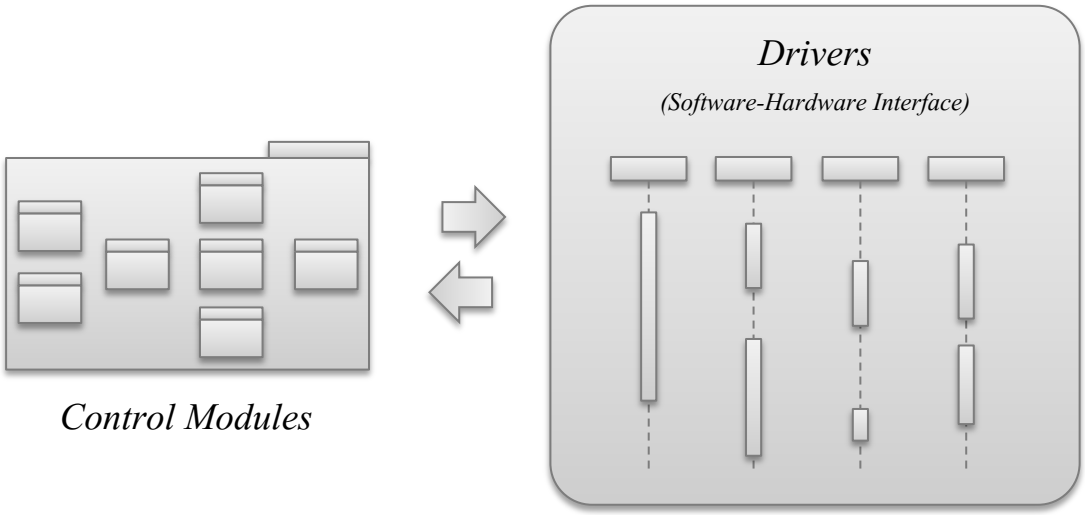
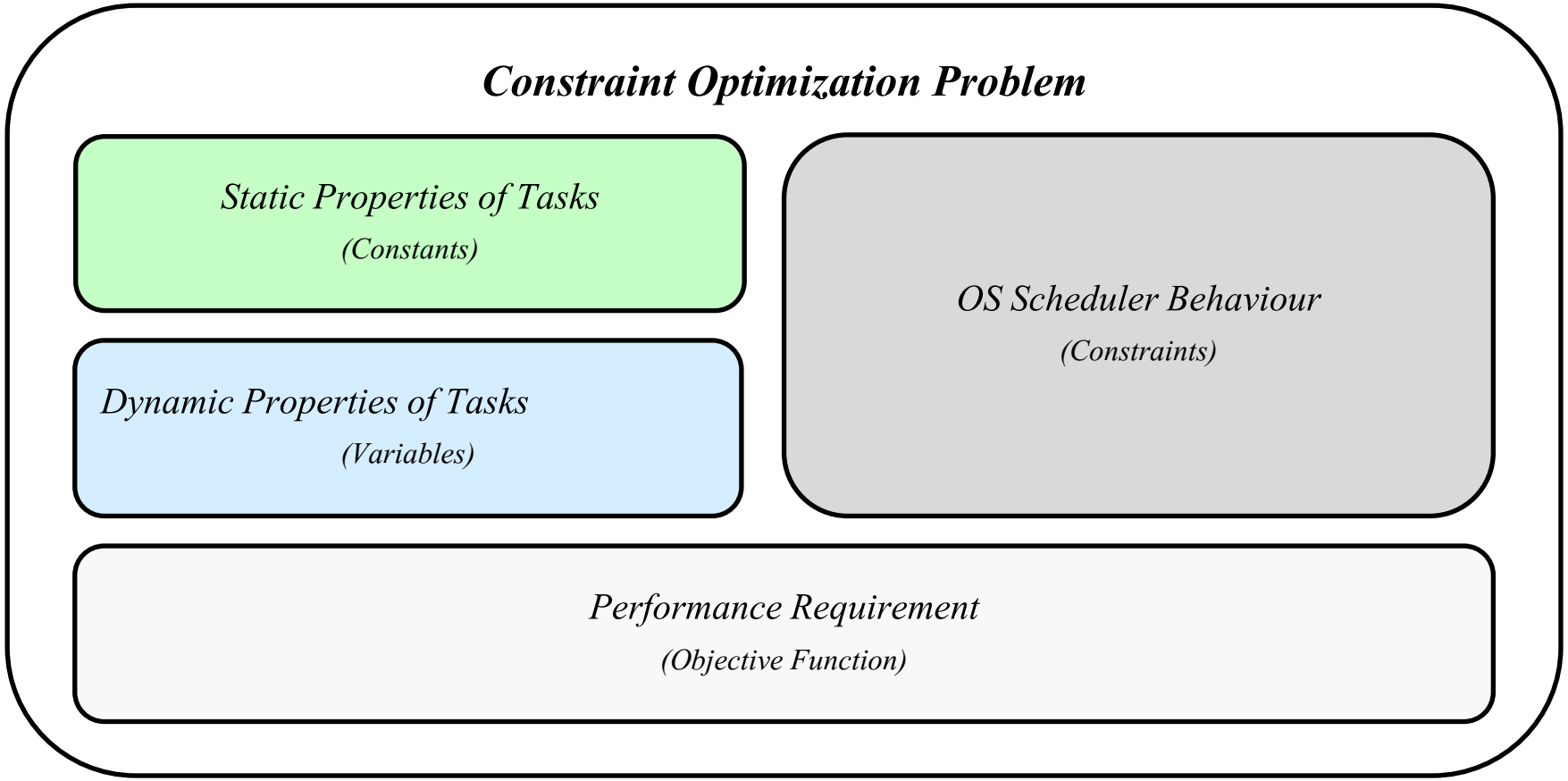
- Ranges for arrival times form a very large input space
- Task interdependencies and properties constrain what parts of the space are feasible
- We re-expressed the problem as a constraint optimisation problem
- Constraint programming (e.g., IBM CPLEX)

Context

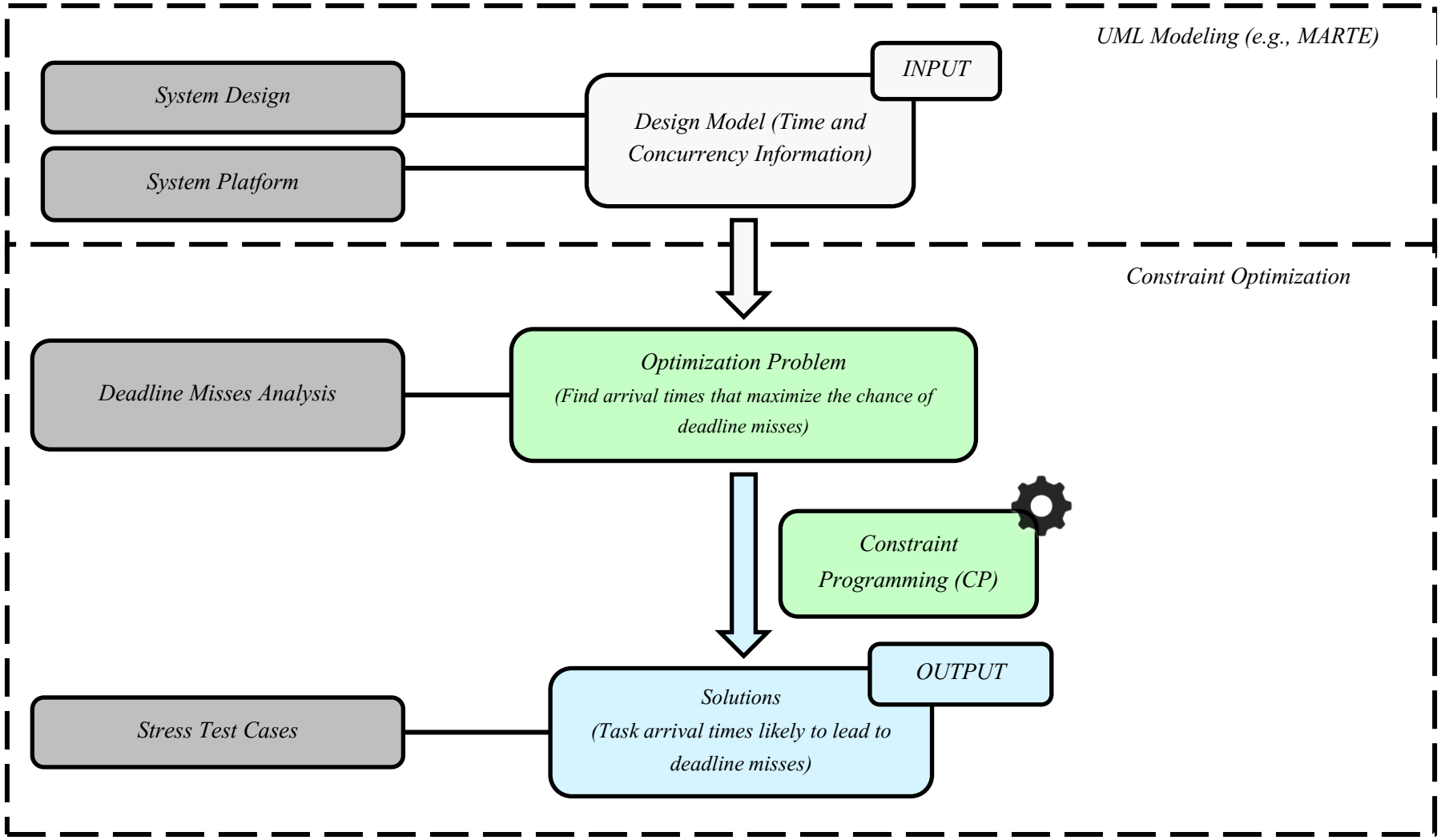
System monitors gas leaks and fire in oil extraction platforms



Constraint Optimization



Process and Technologies



Challenges and Solutions

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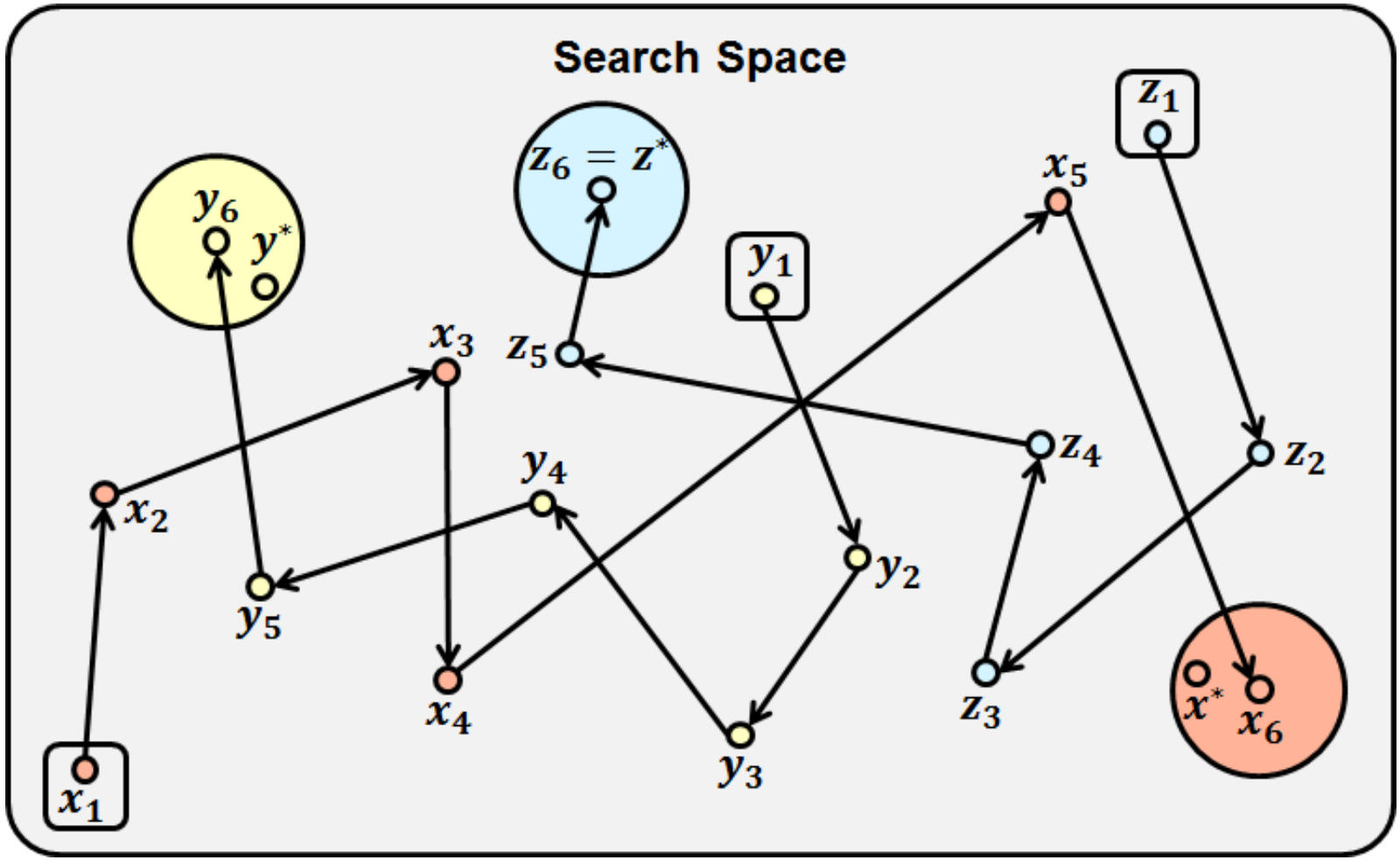
- Scalability problem: Constraint programming (e.g., IBM CPLEX) cannot handle such large input spaces (CPU, memory)

- Solution: Combine metaheuristic search and constraint programming
  - metaheuristic search identifies high risk regions in the input space
  - constraint programming finds provably worst-case schedules within these (limited) regions
  - Achieve (nearly) GA efficiency and CP effectiveness

Combining CP and GA



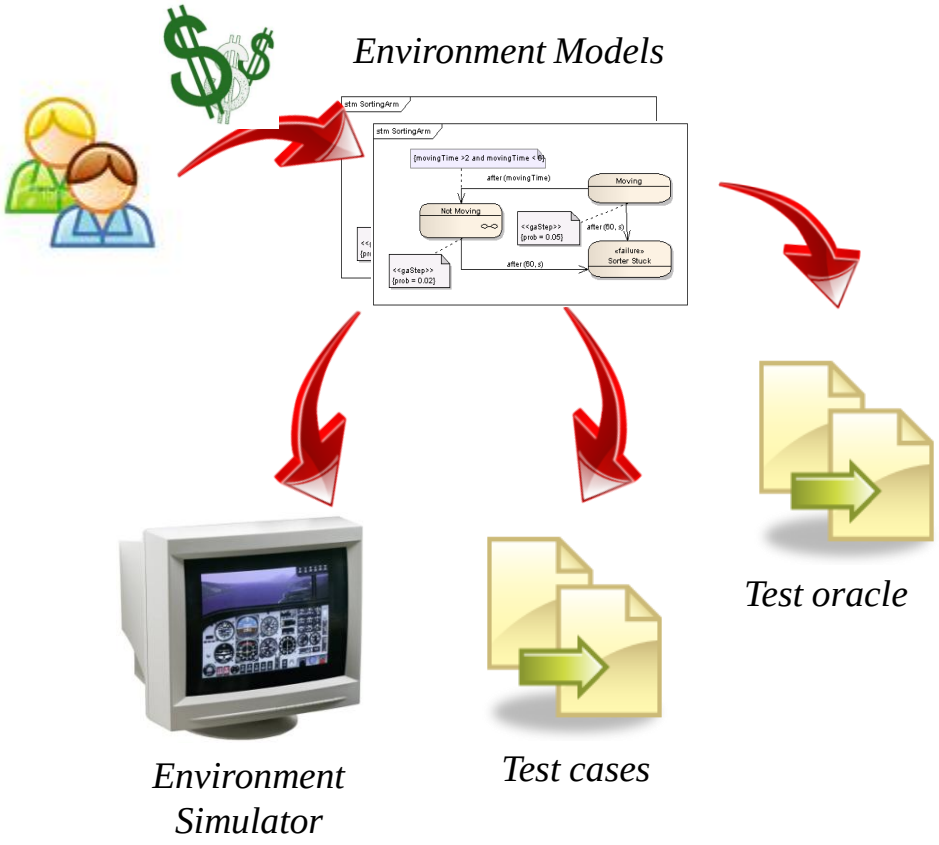
Environment-Based Testing of Soft Real-Time Systems

References:

- *Z. Iqbal et al., "Empirical Investigation of Search Algorithms for Environment Model-Based Testing of Real-Time Embedded Software", ACM ISSTA, 2012*
- *Z. Iqbal et al., "Environment Modeling and Simulation for Automated Testing of Soft Real-Time Embedded Software", Software and System Modeling (Springer), 2014*

Objectives

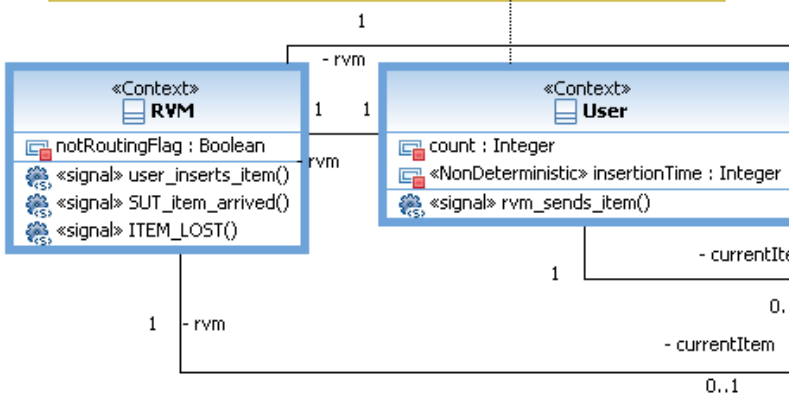
- Model-based system testing
  - Independent test team
  - Black-box
  - Environment models

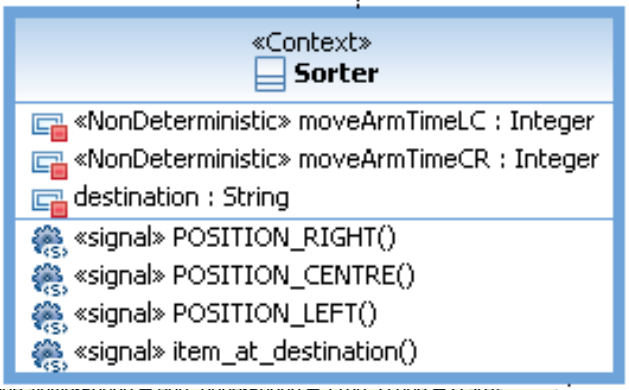


Environment: Domain Model

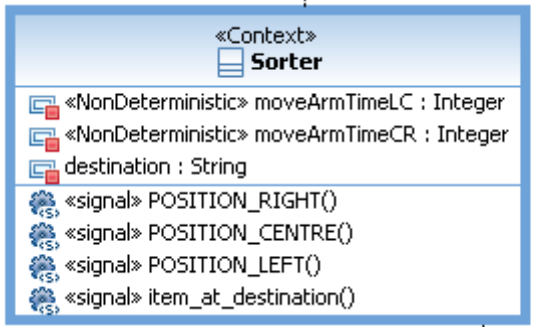
«NonDeterministic»
User::insertionTime {lowerBound = 1, upperBound = 10000, scope = state}

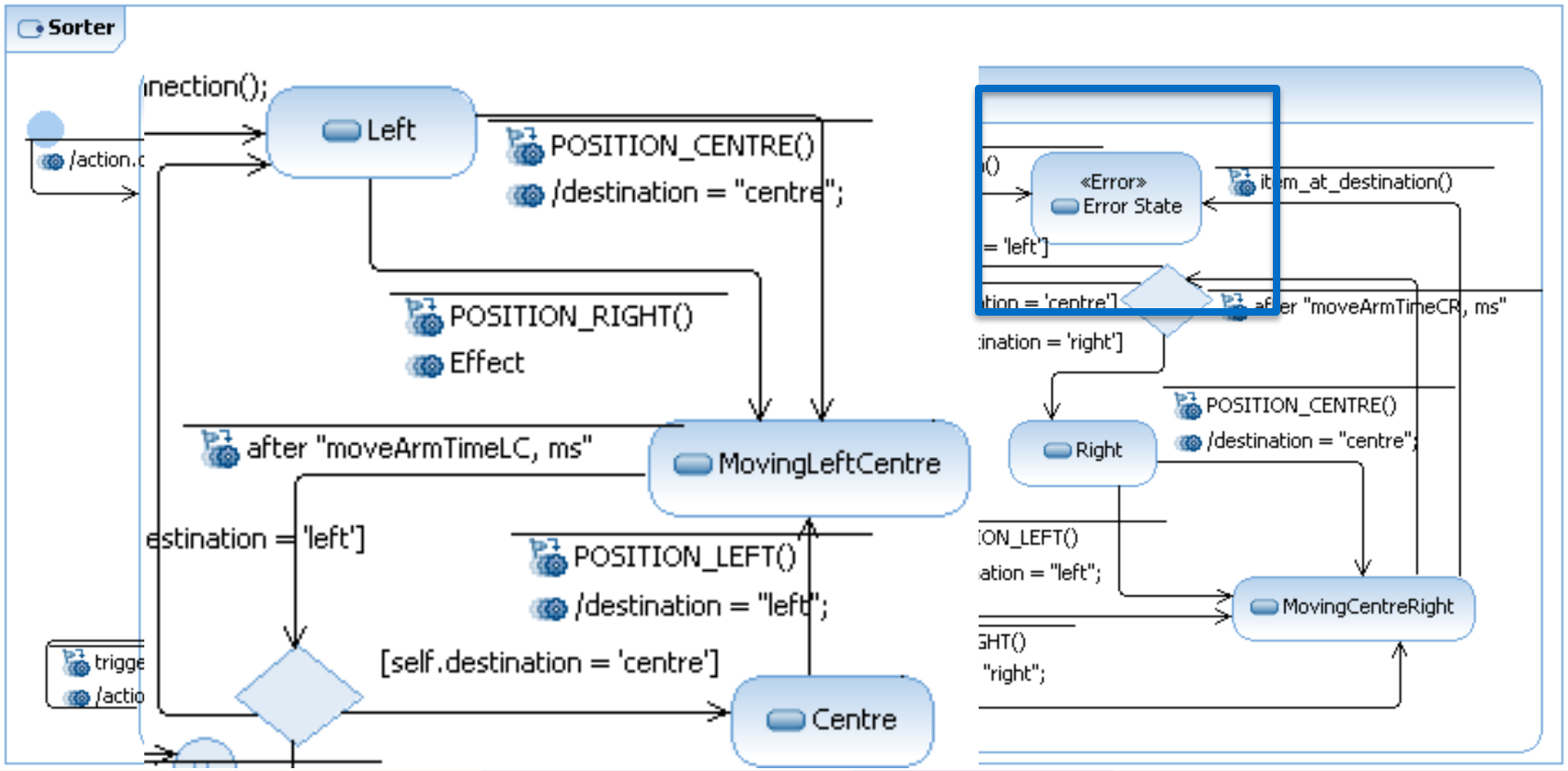
«NonDeterministic»
Sorter::moveArmTimeLC {lowerBound = 280, upperBound = 320, scope = state}
Sorter::moveArmTimeCR {lowerBound = 280, upperBound = 320, scope = state}





Environment: Behavioral Model





Test Case Generation

- Test objectives: Reach “error” states (critical environment states)
- Test Case: (1) Environment and (2) Simulation Configuration
  - (1) Number of instances for each component in domain model, e.g., number of items on conveying belt
  - (2) Setting non-deterministic properties of the environment, e.g., speed of sorter’s left and right arms
- Oracle: Reaching an “error” state
- Metaheuristics: search for test cases getting to error state
- Fitness function
  - Distance from error state
  - Distance from satisfying guard conditions
  - Time distance
  - Time in “risky” states

Stress Testing focused on Concurrency Faults

Reference:

M. Shousha et al., "A UML/MARTE Model Analysis Method for Uncovering Scenarios Leading to Starvation and Deadlocks in Concurrent Systems", IEEE Transactions on Software Engineering 38(2), 2012

Stress Testing of Distributed Systems

Reference:

V. Garousi et al., "Traffic-aware Stress Testing of Distributed Real-Time Systems Based on UML Models using Genetic Algorithms", Journal of Systems and Software (Elsevier), 81(2), 2008

General Pattern: Using Metaheuristics

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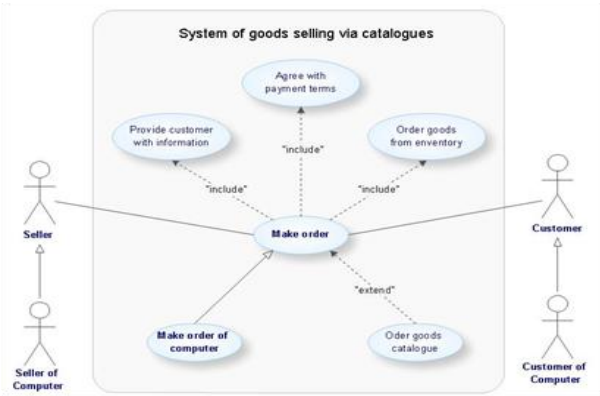
Model



Problem

Objective Function

Search Space

Search Technique

- *Search to optimize objective function*
- *Metaheuristics, constraint programming*
- *Scalability: A small part of the search space is traversed*
- *Model: Guidance to worst case, high risk scenarios across space*
- *Reasonable modeling effort based on standards or extension*
- *Heuristics: Extensive empirical studies are required*

Scalability

Project examples

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- Scalability is the most common verification challenge in practice

- Testing closed-loop controllers
  - Large input and configuration space
  - Smart heuristics to avoid simulations (machine learning)
- Schedulability analysis and stress testing
  - Large space of possible arrival times
  - Constraint programming cannot scale by itself
  - CP was carefully combined with genetic algorithms

Scalability: Lessons Learned

- Scalability must be part of the problem definition and solution from the start, not a refinement or an after-thought
- Meta-heuristic search, by necessity, has been an essential part of the solutions, along with, in some cases, machine learning, statistics, etc.
- Scalability often leads to solutions that offer “best answers” within time constraints, but no guarantees
- Scalability analysis should be a component of every research project – otherwise it is unlikely to be adopted in practice
- How many papers research papers do include even a minimal form of scalability analysis?

Applicability

Project examples

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- Applicability requires to account for the domain and context

- Testing controllers
  - Relies on Simulink only
  - No additional modeling or complex translation
  - Within domains, differences have huge implications in terms of applicability (open versus closed loop controllers)
- Minimizing risks of CPU shortage
  - Trade-off between between effective synchronisation and CPU usage
  - Trade-off achieved through multiple objective GA search and appropriate decision tool
- Schedulability analysis and stress testing
  - Near deadline misses must be identified

Applicability: Lessons Learned

- In software engineering, and verification in particular, just understanding the real problems in real contexts is difficult
- What are the inputs required by the proposed technique?
- How does it fit in development practices?
- Is the output what engineers require to make decisions?
- There is no unique solution to a problem as they tend to be context dependent, but a context is rarely unique and often representative of a domain

Discussion

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- Metaheuristic search
  - Tends to be versatile, easy to tailor to a new problem
  - Entails acceptable modeling requirements
  - Can provide “best” answers at any time
  - Scalable

  But
  - Not a proof, no certainty
  - Though in practice (complex) models are not fully correct, there is no certainty anyway
  - Effectiveness of search guidance is key and must be experimented and evaluated
  - Models are key to provide adequate guidance

Talk Summary

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- Focus: Meta-heuristic Search to enable scalable verification and testing.
- Scalability is the main challenge in practice.
- Drew lessons learned from example projects in collaboration with industry, on real systems and in real verification contexts.
- Results show that meta-heuristic search contributes to mitigate the scalability problem.
- It has shown to lead to applicable solutions in practice.
- Solutions are very context dependent.
- It is usually combined with a variety of other complementary techniques: system modeling, constraint solving, machine learning, statistics.

Scalable Software Testing and Verification Through Heuristic Search and Optimization

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