Challenges for Testing Autonomous Driving Systems:

Tackling Uncertainty in the Open Physical World and Machine Learning

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ERATO MMSD

QAML

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About Speaker

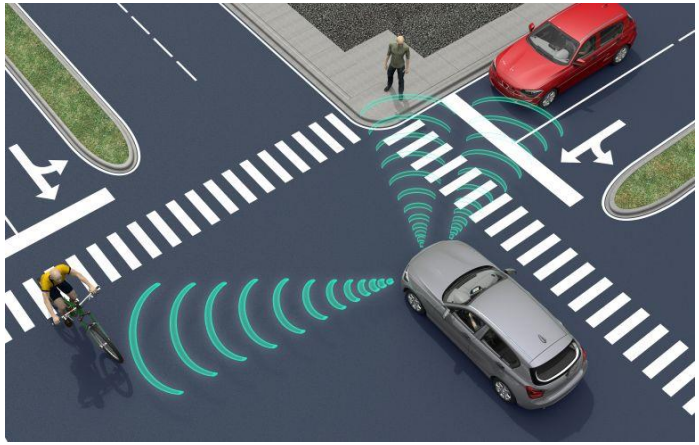
- Was not really a testing researcher
  - Quality by optimization (web services, clouds)
  - Formal engineering methods (VDM/Event-B/Alloy)
  - A little on testing (previously a kind of adaptive testing)
- Current focus (1): dependability of (autonomous) driving systems

  Today's core topic: testing is the key
- Current focus (2): dependability of machine learning-based systems

  (tomorrow at MLST)

Smart CPS

- Smart Cyber-Physical Systems



  - Continuous aspects (requirements, environment, and system behavior)
  - Use of machine learning

Our ERATO-MMSD Project for Dependable CPS

Group 0: Metamathematical Integration

$T \quad + \quad e \quad \rightarrow \quad T(e)$

Category Theory

led by Ichiro Hasuo (NII) (2016-2022)

Group 1: Heterogenous Formal Methods

$T_1 \quad + \quad e_1 \quad \rightarrow \quad T_1(e_1)$

$T_2 \quad + \quad e_2 \quad \rightarrow \quad T_2(e_2)$

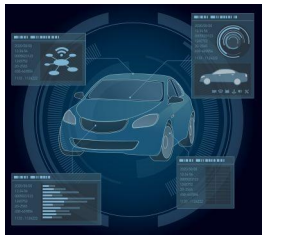
Computer Science

Control Theory

Testing is here!

Group 2: Formal Methods in Industry

Advanced setting in autonomous driving



Automotive Industry

Practical setting to improve present practices

Group 3: Formal Methods and Intelligence

Heuristics, Evolutionary, Search-based approaches

Optimiz ation

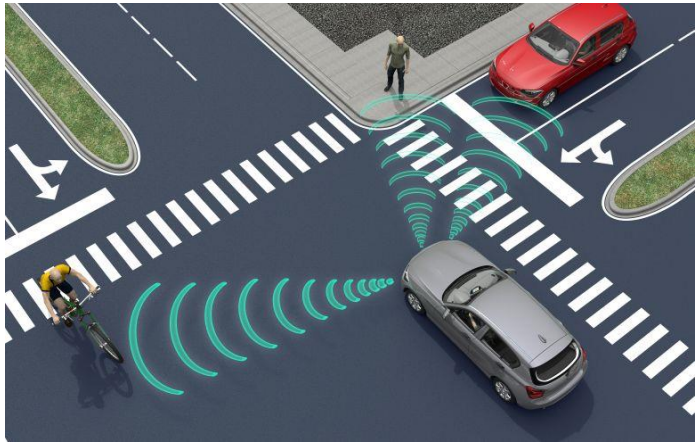
Software Engineering

Machine Learning

Physical World, Modeling?

Smart CPS: Physical

- Smart Cyber-**Physical** Systems



- Continuous dynamics
- Differential/Difference equations
- Quantitative goals
  (distance, energy, probability, etc.)

[Lee, Cyber-Physical Systems - Are Computing Foundations Adequate?, 2006]

Rigorous Modeling for CPS

- Scope beyond the classical software science
  - Hybrid models with not only discrete dynamics but also continuous dynamics for speed, energy, electricity, etc.

➡ **Heterogenization** or **quantification** of "models" in software science and engineering (e.g., formal modeling and verification)

  - Modeling and verification of energy consumption [Nakajima, FM'15]
  - SMT Solver for nonlinear real formulas [Gao, CADE'13]
  - Hybrid "program" logic and theorem proving [Platzer, IJCAR'08]
  - Hybrid automata, co-modeling/simulation, …

Example: Differential Dynamic Logic

- Differential dynamic logic

"Program" including state changes by differential equations

$$x<=m \ \wedge \ C(x,v) \ \ [a:=-b; \ (x'=v; \ v'=a)] \ \ x<=m$$

Precondition on position *x* and velocity *v*

Deaccelerated by braking -b

Not go beyond the position *m*

$C \equiv v^2<=2b(m-x)$

by discriminant

[Platzer, Logical Analysis of Hybrid Systems: Proving Theorems for Complex Dynamics, 2010]

Pragmatic Solution?

- Heterogenized verification is sometimes infeasible

  (as happened even for the discrete settings)

  - Not scalable, or just undecidable
  - Mathematically rigorous models often unavailable

    (e.g., Simulink models without clear semantics

    or just too complex controller simulators)

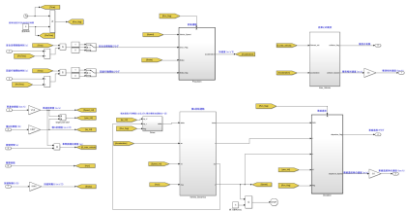
➡ *We know testing as a pragmatic solution!*

But what from the formal community?

 # I'm not saying the communities are disjoint

Typical Setting

Simulink model of car behavior with automated braking



Inputs

User Behavior
- Throttle signals
- Brake signals

Environment Condition
- Initial velocity
- Location and movement of pedestrian
- Road conditions
- …

Outputs

- Hit a pedestrian?
- Speed if hit

- *We have executables (simulation models or code)*
- *At least we can execute it to evaluate the output for a certain input*

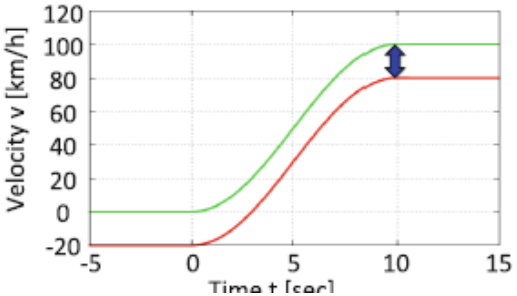
➡ *Any "dangerous" case?*

Physical World, “Testing”!

One Trend: Optimization-Driven Falsification

■Quantified properties

2 sample simulations



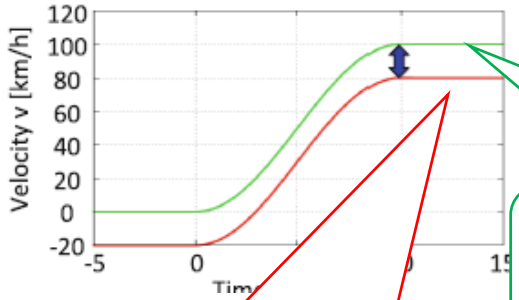
The velocity becomes ***<u>>= 80 km/h</u>***
<u>within 10 seconds</u> *after B occurs?*

[Fainekos et al., Robustness of temporal logic specifications for continuous-time signals, TheoCompSci'09]
Figure from [Akazaki et al, Time Robustness in MTL and Expressivity in Hybrid System Falsification, CAV'15]

One Trend: Optimization-Driven Falsification

■Quantified properties quantitatively evaluated

2 sample simulations



The velocity becomes ***<u>>= 80 km/h</u>***
<u>within 10 seconds</u> *after B occurs?*

YES, after 10 seconds +20km/h than required!

Robust Satisfaction

YES, after 10 seconds exactly the required value!

Fragile Satisfaction (close to Violation)

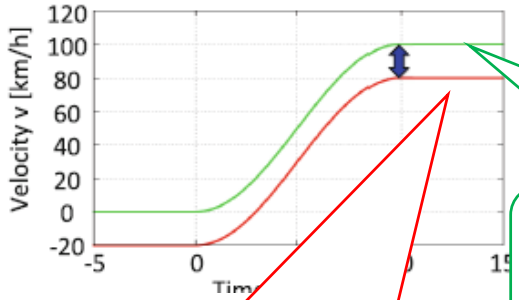
(similar evaluation can be done for time, too)

[Fainekos et al., Robustness of temporal logic specifications for continuous-time signals, TheoCompSci'09]
Figure from [Akazaki et al, Time Robustness in MTL and Expressivity in Hybrid System Falsification, CAV'1]

One Trend: Optimization-Driven Falsification

■Falsification of quantified properties

2 sample simulations



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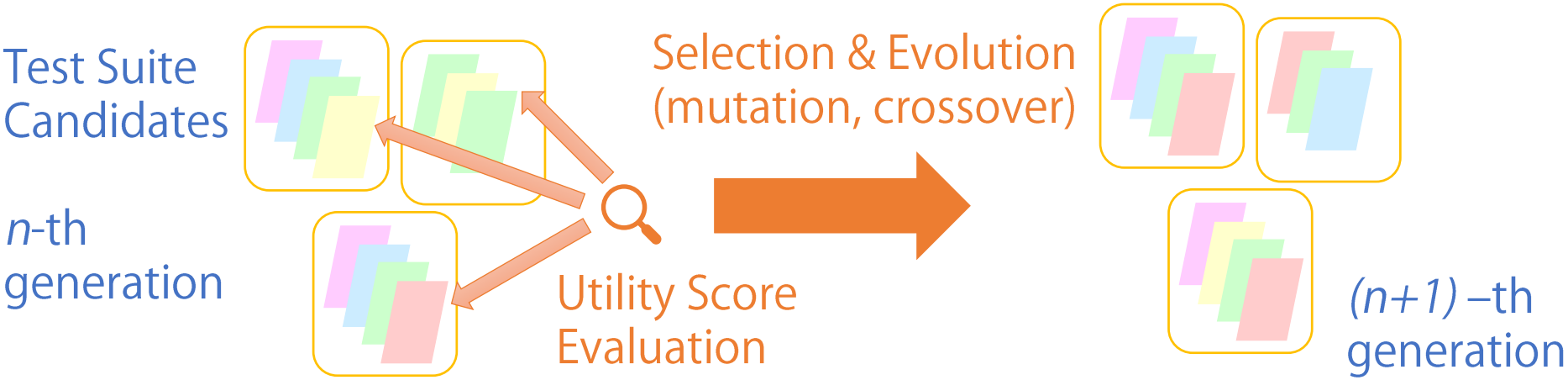
➡ *Optimization of "robustness score"*

■e.g., solved by "trials-evaluation" cycles

[Fainekos et al., Robustness of temporal logic specifications for continuous-time signals, TheoCompSci'09]
Figure from [Akazaki et al, Time Robustness in MTL and Expressivity in Hybrid System Falsification, CAV'15]

We Know This Kind: Search-based Testing

- Use of metaheuristic for test generation
  - Again, "trials-evaluation" cycles
  - Used also for generating a "good" test list/suite/vector

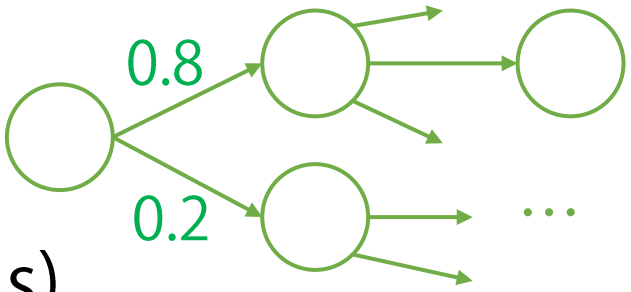


  - e.g., 10 min. to produce the "same-level" test suite as human (in terms of code coverage and mutation score)
  - e.g., use in Facebook (Sapienz)

[Molina et al, Java Unit Testing Tool Competition - Sixth Round]
[https://code.fb.com/developer-tools/sapienz-intelligent-automated-software-testing-at-scale/]

Another Trend: Statistical Model Checking

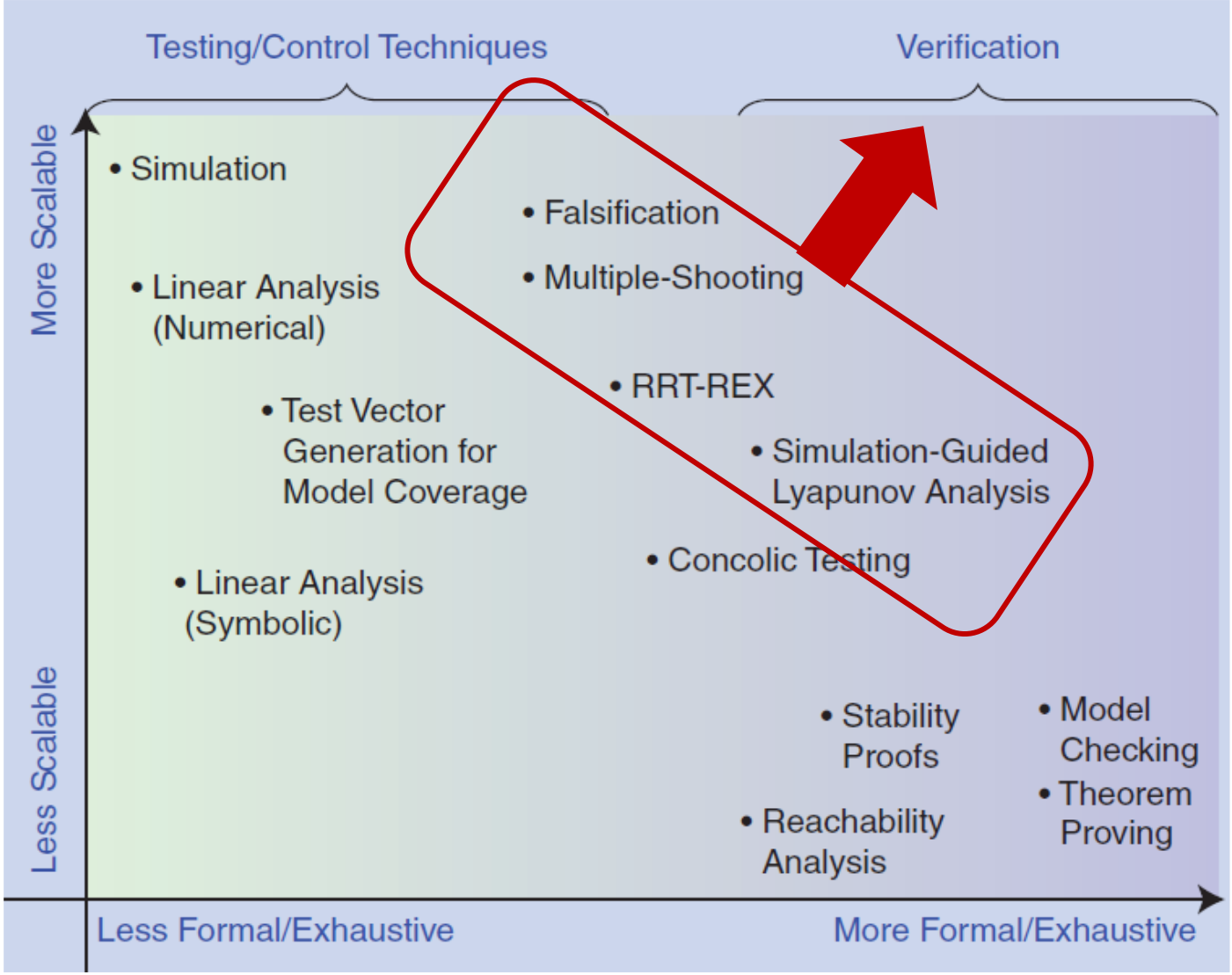
- Computational models with probabilities
- ➡ "Probability calculation" of (un)desirable situations is too heavy (e.g., on Marcov models)



- ➡ *Hypothesis testing* or *probability estimation* by a lot of trials (executions/simulations)
  - Capability (and demand) to tailor to the problem by using prior knowledge on the domain/problem

[Jha et al., A Bayesian Approach to Model Checking Biological Systems, CMSB'11]
[Zuliani et al, Bayesian statistical model checking with application to Stateflow/Simulink verification, FMSD'13]

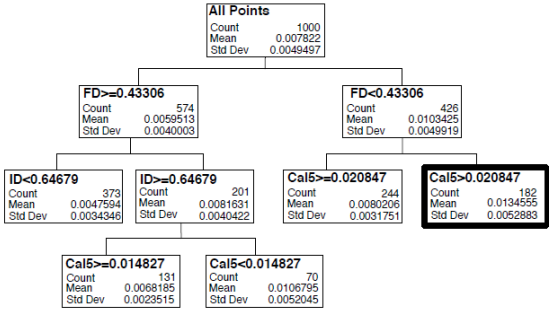
A Spectrum for Control Systems



[Simulation-Based Approaches for Verification of Embedded Control Systems, IEEE Control Mag.'16]

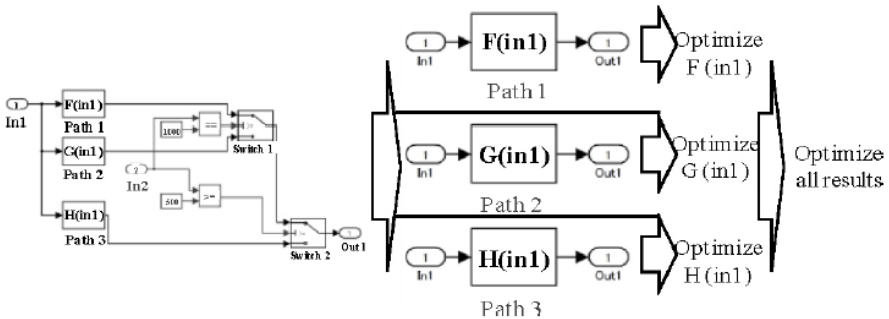
Example Topics in SBT

- Targeting Simulink models
  - Construct a "heat map" of the global space for focused search and also learn the scoring function to avoid many costly simulation runs



[R. Matinnejad, et al., MiL Testing of Highly Configurable Continuous Controllers: Scalable Search Using Surrogate Models, 2014]

  - Use formal techniques to divide the search space



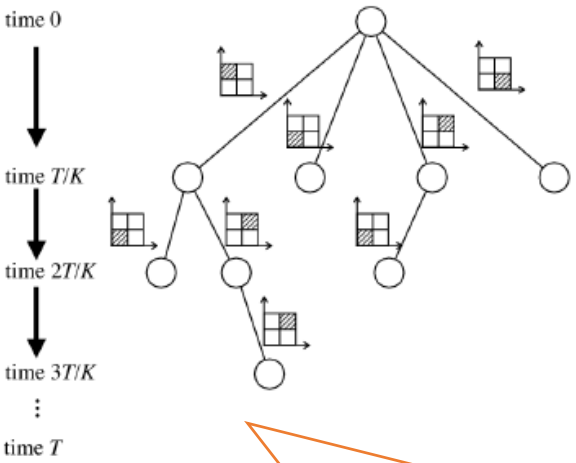
[S. Kobuna, et al., Validation of Control Software by Search-Based Testing Using Formal Methods, 2016]

Our Example: More Exploratory Falsification

- Apply a systematic exploration method
  - Avoid local optima (too much exploitation)
  - Also obtain informative data on the search space

➡ Monte-Carlo Tree Search

- Common for bandit problems, AI Go game player, etc.
- Used to record the "smells" over the search space (time-staged) in the "trials-evaluation" cycles



What about making full throttle in the first time slot, ⋯

[Zhang et al., Two-Layered Falsification of Hybrid Systems Guided by Monte Carlo Tree Search, EMSOFT/TCAD'18]

Our Example: Falsification by Training

- Learn of how to falsify
  - Avoid search from scratch for every check
- Target a product family
  - Quick check during trial-and-error or for updates
  - Not only design parameters but also environmental parameters

[Kato et al., Falsification of Cyber-Physical Systems with Reinforcement Learning, MT-CPS'18]

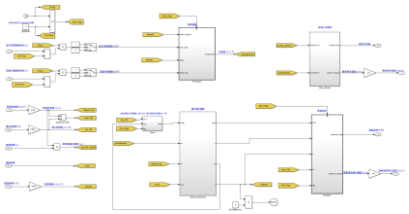
Summary at This Point

- More and more focus on “testing” or simulation-based approaches to CPS dependability

Your contributions with testing expertise will be really appreciated!

Typical Setting: Revised

Simulink model of car behavior with automated braking



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- Road conditions
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Outputs

- Hit a pedestrian?
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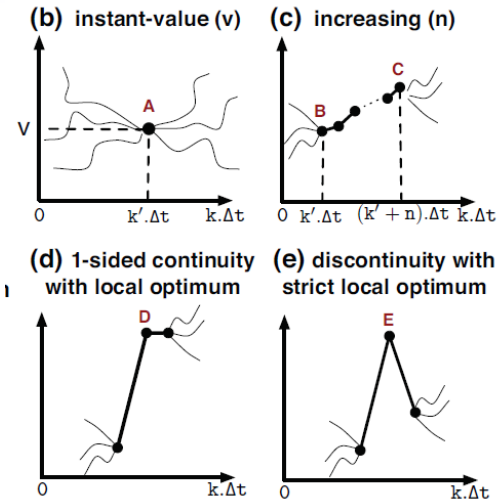
- *We have executables (simulation models or code)*
- *At least we can execute it to evaluate the output for a certain input*

➡ *Any useful problem settings & solution techniques?*

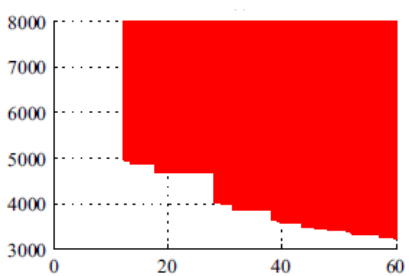
Topic Examples: Broader "Testing"

- Generate a test suite that includes "diverse" shapes of output signals for human investigation

[R. Matinnejad, et al., Automated Test Suite Generation for Time-continuous Simulink Models, 2016]



- Specification mining (pareto-front search)
  - Search for formulae (in a given form) not satisfied



$$\neg\ (\text{within time } t0\ (v\ \geq 100)\ \wedge\ \text{always}\ (w\ \leq w0)\ )$$

[B. Hoxha, et al., Mining parametric temporal logic properties in model-based design for cyber-physical systems, 2018]

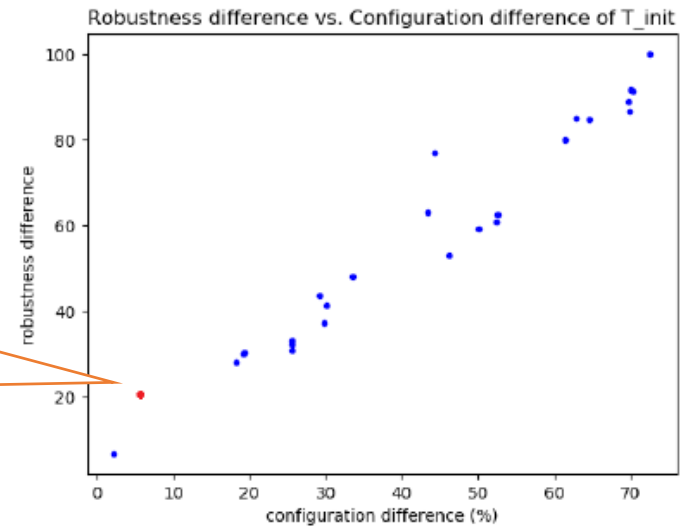
Our Example: Stability Analysis

- Search for "unstable" areas of parameter values

  "Small changes of parameter values affect the safety score a lot"

  - About design parameters (avoid or test intensively) and about environmental parameters (test intensively)

0.12 sec. difference in the initial kick-off changes non-crash to a 20km/h crash



[Lee et al., Stability Analysis for Safety of Automotive Multi-Product Lines: A Search-Based Approach, GECCO'19]

Summary at This Point

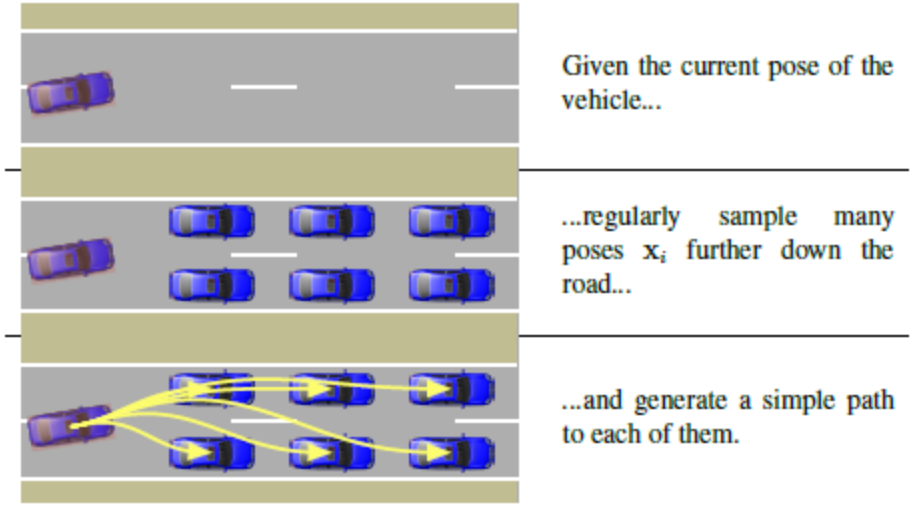
- More and more focus on “testing” or simulation-based approaches to CPS dependability
- Complexity and uncertainty of various kinds
  - Approaches not limited to find “faulty” cases

Your contributions with testing expertise will be really appreciated!

Open World, System-Level

System-Level Example: Path Planner

- A component to decide the path of the ego-car



[Figure from McNaughton, Parallel Algorithms for Real-time Motion Planning]

- For the short term or the long term, anyway deciding the immediate control operations
- Imagine a simple one by optimizing the cost function: including distance with obstacles, lane conformance, limitation in possible behavior, comfort, etc.

Let's Generate Test Cases!

- Space of parameters for a test case
- ➡ *Defined naively or at least bounded by possible configurations of the simulator*
- Design parameters (fixed this time)
  - Weights in the cost function
- Environmental parameters
  - Road structure and behavior of signals
  - Weights, wheel size, etc. of the ego-car
  - Position and movement of other cars and pedestrians

Demo: First Example

- A possible configuration
  and a possible car behavior

(demo omitted in this online version: the ego-car just goes straight, almost but not crashing with a lot of other cars that go orthogonally to the ego-car)

What's "Strange"?

- "Cars crossing the street"?
  - But this can reasonably occur, e.g., a car moving from a shopping mall to a restaurant at the opposite side
  - Then, "too many", which is too rare (almost impossible)
  - ➡ *So, what is the (model of) assumptions?*
- Was the test "pass" or "fail" (if it is valid)?
  - No crash, very efficient, and (physically) comfortable
  - Not so safe (too close to other cars)
  - ➡ *Naturally considered by the quantified verification*
  - Not appropriate in terms of the driving convention
  - ➡ *So, what is the (model of) oracle?*

More Focus on “Scenarios”

- Think of “scenarios” or “situations” rather than the whole possibilities
  - e.g., Ego-car stops properly for a Jaywalking pedestrian
  - At least necessary for manual test design
  - e.g., in Pegasus project

    [https://www.pegasusprojekt.de/en/about-PEGASUS]
  - e.g., in Open Autonomous Safety

    [https://oas.voyage.auto/]
  - Difficulties remain in defining a valid parameter space that matches with the intention of the scenario and also (often implicit) environmental assumptions

From Open Autonomous Safety

Ego approaches jaywalking pedestrian on undivided road

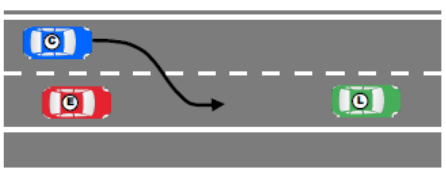
A		**Scenario** Ego approaches pedestrian. Pedestrian stands on side of the road. **Expected Result** Ego reduces speed.
B		**Scenario** Pedestrian enters roadway. **Expected Result** Ego comes to a stop in front of pedestrian.
C		**Scenario** Pedestrian exits the road. **Expected Result** Ego proceeds.
D		**Scenario complete** 🎉

[https://oas.voyage.auto/scenarios/pedestrians-in-road.html]

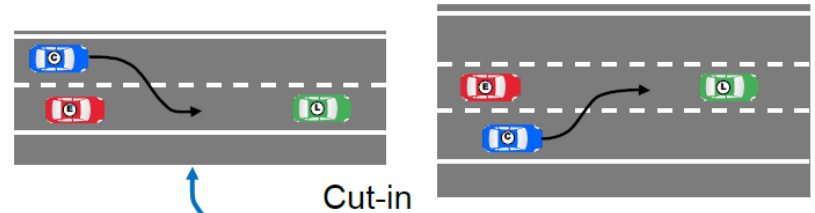
From Pegasus

Cut-in

- Start situation
  - Ego car (**E**) drives on highway lane
  - Other vehicle (**C**) on adjacent lane
  - Potentially further vehicles involved
- Evolution
  - **C** moves into E-lane in front of **E**
- Criticalities
  - **C** cuts in with little distance to **E**
  - **C** brakes after cutting in
  - Low TTC(**E**,**C**)



TTC: Time to collision



Cut-in (left, from behind) (regular traffic situation)

- Step 1:
  - Velocity [m/sec]: E , L: [22-36]; E-L: [-4,4]; C: [23-67]; C-E: [1,45];
  - Position [m]: L-E: [33,100]; E-C: [0,30];
  - Distributions: may be multivariate binomial (nontrivial correlations), or multivariate gamma-distributions
  - …
- Step 2: Cut-in starts (C crosses lane marking) Δt: [2,20]
  - Velocity [Δ m/sec]: L: [-7,+7]; C: [-50,+5]; C-E: [-5,40]; C-L:[-12,50]
  - Position [m]: L-E: [25,110]; C-E: [1,60]; L-E: [5,100]
  - …
- Step 3: Cut-in completed (C has crossed lane marking halfway) Δt: [0.5,4]
  - Velocity [Δ m/sec]: …
  - …

[Hunger et. al., Test Specifications for Highly Automated Driving Functions: Highway Pilot, 2017
https://www.pegasusprojekt.de/en/information-material?file=files/tmpl/pdf/AVT%20Symposium%202017%20Test%20Specifications%20for%20HAD_Folien%20.pdf]

Demo: Second Example

- How about this?
  - Is this a “strange” case or not?

  If not,
  - How to comprehensively include this kind of scenario?
  - How to reach this specific crash case in the kind of scenario?

(demo omitted in this online version: two cars goes orthogonally to the ego-car, the ego-car succeeds to avoid the first one by changing the path but crashes with the second one)

Application of Existing Methods?

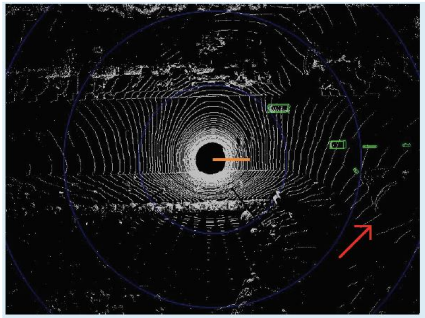
- White-box testing
  - What are coverage criteria to define "important" factors in the implementation?
- Model-based testing
  - For example, what is a model to serve as the foundation for (requirements-based) coverage criteria?
- Mutation analysis
  - What are "bugs" that should be detected in the implementation?

➡ ***We need more focus and insights about models on assumptions, "good" tests, bugs, etc.***

Emerging Efforts

- Metamorphic testing
  - Define the expected output via a metamorphic relation: *"changing an input this way will change the output that way"*
  - (Applied to the sensing part)

[Zhou et. al., Metamorphic Testing of Driverless Cars, 2019]



(b) After adding 1,000 random data points outside the ROI, the three cars inside the ROI could no longer be detected.

- Formal analysis
  - "Responsibility-Sensitive Safety"
  - e.g., exclude "strange cases"

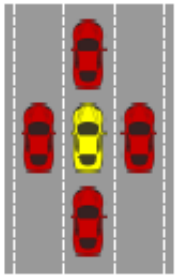


Figure 1: The central car can do nothing to ensure absolute safety.

[Shwartz et. al., On a Formal Model of Safe and Scalable Self-driving Cars, 2017]

Summary at This Point

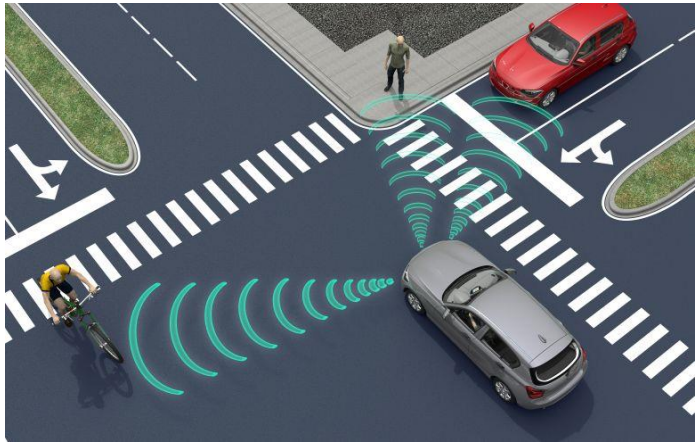
- More and more focus on "testing" or simulation-based approaches to CPS dependability
- Complexity and uncertainty of various kinds
  - Approaches not limited to find "faulty" cases
  - Intrinsic high uncertainty in systems that work in the open world with no clear boundaries/criteria

Your contributions with modeling and testing expertise will be really appreciated!

A Little on Machine Learning

Smart CPS: Smart

Smart Cyber-Physical Systems



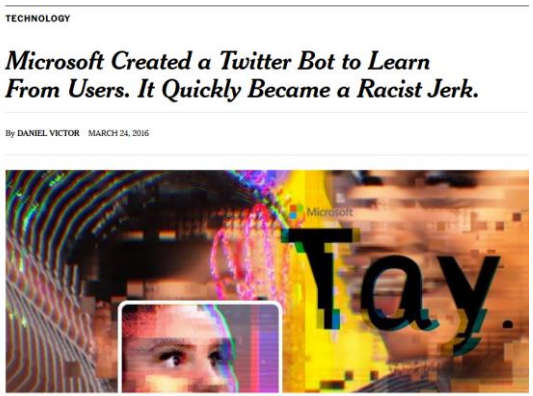
Use of machine learning
- Data-driven development
- Black-box behavior
- Imperfect functionality

AI and ML

- Everyone is talking about AI and ML, recently more about risks and concerns in terms of dependability

Accidents of autonomous cars

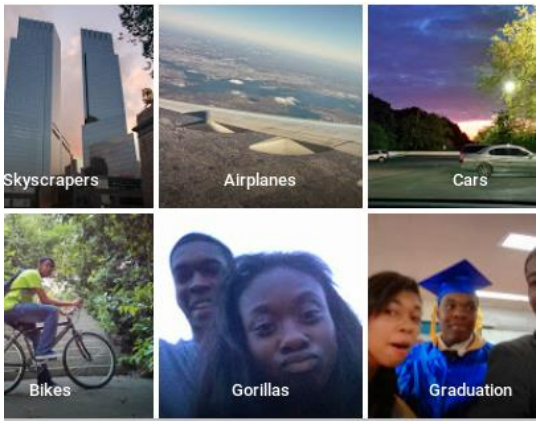
[http://www.dailymail.co.uk/news/article-3677101/Tesla-told-regulators-fatal-Autopilot-crash-nine-days-happened.html]



Improper online learning

[https://www.nytimes.com/2016/03/25/technology/microsoft-created-a-twitter-bot-to-learn-from-users-it-quickly-became-a-racist-jerk.html]

Technically unsolved problems at Google Photo

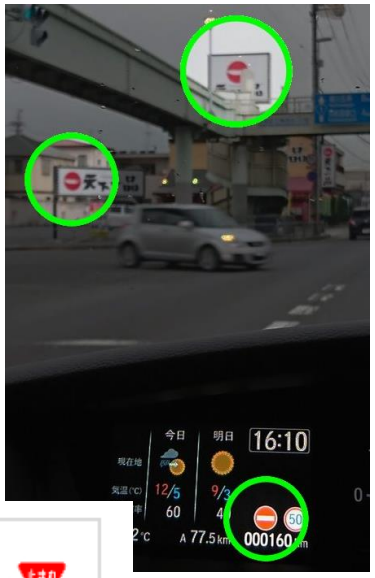


[https://www.theguardian.com/technology/2015/jul/01/google-sorry-racist-auto-tag-photo-app]
[https://www.theguardian.com/technology/2018/jan/12/google-racism-ban-gorilla-black-people]

What will You Test? (1)

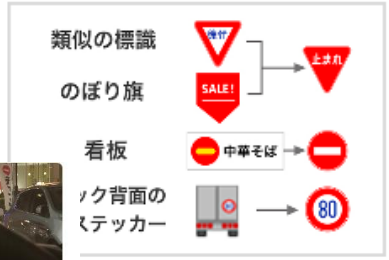
- When Honda sees ramen shop sign
  - First buzz in Dec 2017

    [https://twitter.com/_gyochan_/status/938240168078622720]
    [https://twitter.com/Bleu_kakeru727/status/937680760491753473]



  - Now a caution on the web site

    http://www.honda.co.jp/hondasensing/feature/srf/



色や形の判別が
つきにくく、
象の標識が無いのに、
標識を表示する

  - Second buzz in Sep 2018

8:24 PM - 12 Sep 2018

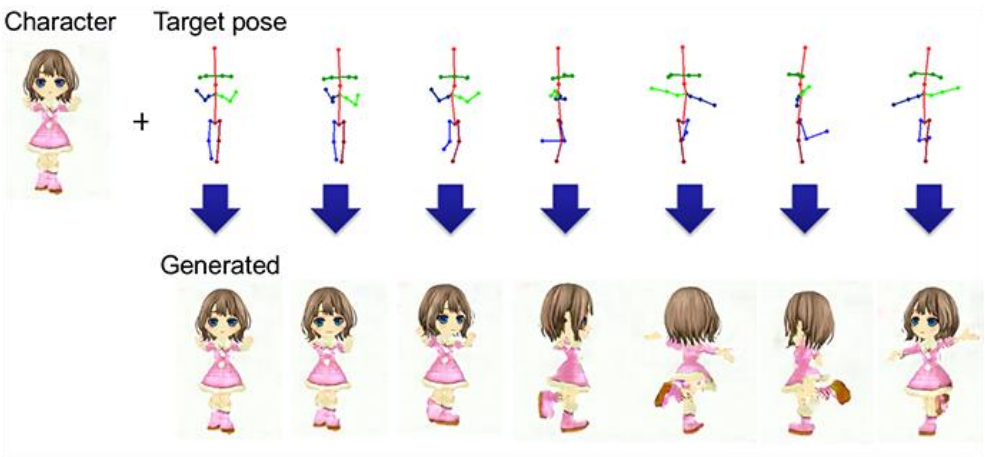
15,099 Retweets 20,908 Likes

/www.tenkaippin.co.jp/
ny.html]

Can you find beforehand or prevent adverse (?) news??

What will You Test? (2)

- From DeNA (May 2018)
  - Generate an image of a certain pose
  - Generate a movie given a pose sequence while changing the character



[https://dena.com/intl/anime-generation/]

What do you ensure to sell this to anime companies?

Essential Difference in ML

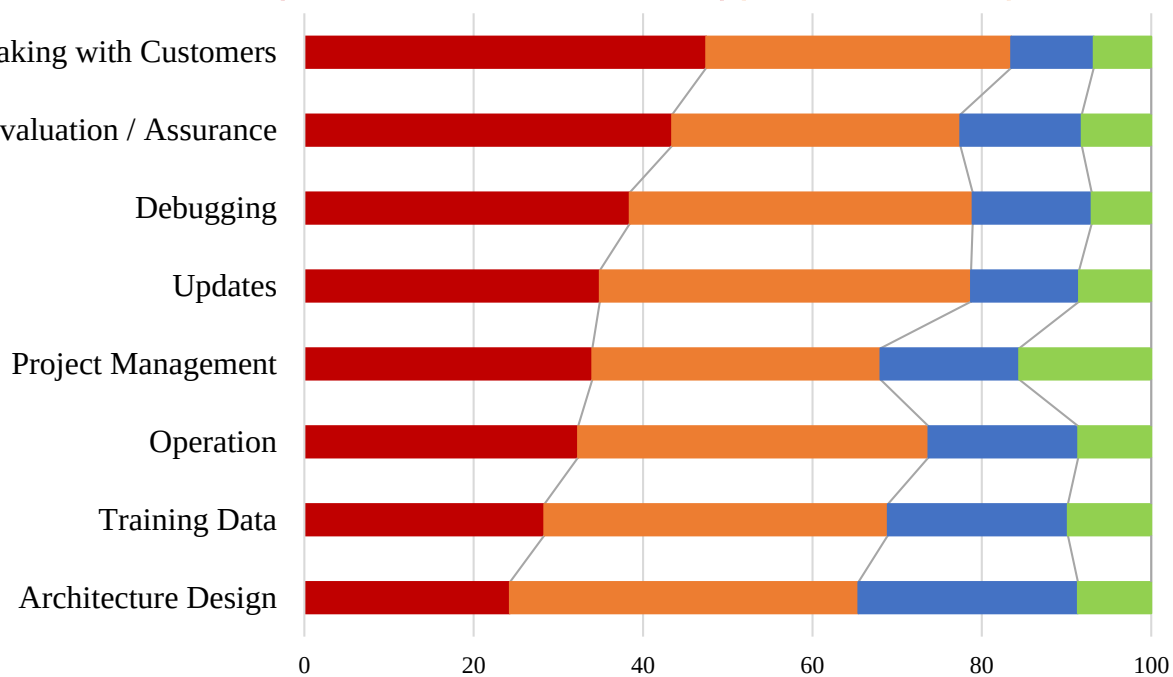
- With ML, we obtain the behavior of a component (e.g., a neural net) **inductively** from training data

  Black-box, imperfect, non-testable (no or costly oracle), unexplainable, has adversarial examples, …

Similar principles but methods unavailable

Existing principles do not work

Especially when arguing the product and its quality

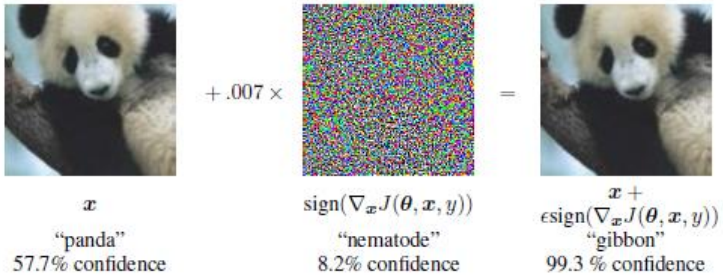


[Ishikawa et al., How do Engineers Perceive Difficulties in Engineering of Machine-Learning Systems? – Questionnaire Survey, CESSER-IP'19]

機械学習工学研究会
MACHINE LEARNING SYSTEMS ENGINEERING

Impacts on Testing (Not Comprehensive)

- Large black-box to handle various situations
  - Principle of unit testing (and debugging) invalidated
- Errors as normal behavior (i.e., not 100% accuracy)
  - Test fail does not mean existence of a bug
- Often non-testable [Weyuker, On Testing Non-Testable Programs, 1982]
  - No oracle or oracle too costly to build
- Unknown boundaries in the implementation, adversarial examples
  - Little confidence on how it works in "similar" cases (no "equivalence classes")



[Goodfellow et al., Explaining and Harnessing Adversarial Examples, 2015]

V&V Research Emerging in SE Community

- SMT-based verification [CAV'17]
- Search for non-robust cases with "neuron coverage" [SOSP'17] [ICSE'18]
- System-level falsification [NFM'17]
- Safe reinforcement learning [AAAI'18]
- Verification by stochastic game [TACAS'18]
- Metamorphic testing case studies [ISSTA'18]
- Empirical study on bug statistics [ISSTA'18]
- Mutation Analysis [ISSRE'18]
- Updated coverage criteria [ASE'18]
- Fairness testing [ASE'18]
- Concolic testing [ASE'18]
- Surprise-driven testing [ICSE'19]
- Demonstration: structural coverage is misleading [ICSE'19]
- (and more) e.g., [https://github.com/TrustAI/Literature-on-DNN-Verification-and-Testing]

Example: White-box Structural Coverage

"How diverse output values of each neuron have been observed by a test suite?"

- Originally used for increasing diversity in the output "bad" (non-robust) cases

  [Pei et al., DeepXplore: Automated Whitebox Testing of Deep Learning Systems, 2017]

  [Tian et al., DeepTest: Automated Testing of Deep-Neural-Network-driven Autonomous Cars, 2018]

- Used as criteria to judge a test suite (dataset)

  [Ma et al., DeepTest: DeepGauge: multi-granularity testing criteria for deep learning systems, 2018]

- Now said "could be misleading"
  - e.g., dependency rather on the search methods
  - e.g., natural inputs vs. adversarial inputs

  [Li et al., Structural Coverage Criteria for Neural Networks Could Be Misleading, 2019]

Summary of This Talk

- More and more focus on "testing" or simulation-based approaches to Smart CPS dependability
- Complexity and uncertainty of various kinds
  - Approaches not limited to find "faulty" cases
  - Intrinsic high uncertainty in systems that work in the open world with no clear boundaries/criteria
  - ML is adding too high complexity and uncertainty even into the implementations we produce

Your contributions with modeling and testing expertise will be really appreciated!

Investigation for essential question: what are "good tests"?