Predictability and Robustness in Embedded Systems

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Based on joint work with Alberto Sangiovanni-Vincentelli.
Complexity Management in Engineering

Model

Artifact

Mathematics
Bridge
Aircraft
Software
etc.

Calculate
Abstract
Predict
Build & test
Mathematical Modeling:
A Tale of Two Cultures

Bridge, Aircraft, etc.:
Physics-based Models
- Differential Equations
- Linear Algebra
- Probability Theory

Software:
Systems-based Models
- Logics
- Discrete Structures
- Automata Theory
Plane makers are accustomed to testing metals and plastics under almost every conceivable kind of extreme stress, but it's impossible to run a big computer program through every scenario to detect the bugs that invariably crop up.

In extreme cases, foul-ups can lead to sudden loss of control, sometimes not showing up until years after aircraft are introduced into service. Malaysia Airlines Flight 124 is a case in point. Boeing's 777 jets started service in 1995 and had never experienced a similar emergency before.

[Wall Street Journal; May 30, 2006]
What’s wrong with our models?

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What’s wrong with our models?

Bridge, Aircraft, etc.: Physics-based Models

Theories of estimation.
Theories of sensitivity.

Artifacts are physical objects; we want to make them predictable and robust.

Software: Systems-based Models

Theories of correctness.

Fallacy: systems are non-physical, pseudo-mathematical objects; we want to prove properties.
Current State of Affairs

Most of Computer Science has systematically removed real time and resource consumption from its programming abstractions.
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Most of Electrical Engineering pretends there is no choice between (i) automatically synthesizing code from high-level, resource-aware models and (ii) low-level (assembly) coding.
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Most of Electrical Engineering pretends there is no choice between (i) automatically synthesizing code from high-level, resource-aware models and (ii) low-level (assembly) coding.

All three approaches (high-level programming, code synthesis, low-level coding) lead to “build & test & tweak”:

Software is the most costly, least flexible, and most error-prone part of an embedded system.
Complexity Control

Traditional Answer:

We need to divide-and-conquer: components, contracts, interfaces, modularity, assume-guarantee, separation of concerns, etc.
Complexity Control

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It has not yet been demonstrated that these approaches simplify the problem; in fact, they often make it more complicated [Lamport].
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It has not yet been demonstrated that these approaches simplify the problem; in fact, they often make it more complicated [Lamport].

*Let’s try something simpler first:*

1. Let’s restrict ourselves to deterministic designs.
2. Let’s restrict ourselves to continuous designs.
Where have all the smart guys gone?
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Software truly is the most complex artifacts mankind builds. It’s not surprising we rarely get it right.

Between $10^{69}$ and $10^{81}$ atoms in the universe.

10 MB cache > $10^{20,000,000}$ states.
Challenge 1:
Build Predictable Systems
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Predictable = Deterministic

A system is *deterministic* if for every input behavior, the output behavior is unique.
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A system is *deterministic* if
for every input behavior, the output behavior is unique.

- internal (invisible) behavior need not be unique
- visible behavior includes all aspects of interest:
  for real-time systems, behavior includes time stamps
Nondeterminism

Central to complexity theory: P v. NP

Central to abstraction:

- high-level programming languages: e.g. memory management
- algorithm design: as long as there exists an $0 \leq i < n$ such that $a[i] > a[i+1]$, swap $a[i]$ and $a[i+1]$
- don’t cares: if input = 0, then output = ⊥

Central to concurrency: $a || b = ab + ba$
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Output domain = $\{0, 1, \bot\}$
Nondeterminism

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Central to concurrency: $a || b = ab + ba$

- $a$: $x := x+1$
- $b$: $x := 2x$
Nondeterminism

Central to complexity theory: P v. NP

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  - high-level programming languages: e.g. memory management
  - algorithm design: as long as there exists an $0 \leq i < n$ such that $a[i] > a[i+1]$, swap $a[i]$ and $a[i+1]$
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Central to concurrency: $a || b = ab + ba$

Alternatives to threads:
  actors; transactions

less nondeterministic
Nondeterminism

1. Input nondeterminism: OK
   for every observable input behavior,
   unique observable output behavior

2. Unobservable implementation nondeterminism: OK
   deterministic abstraction layer over nondeterministic components

3. Don’t care nondeterminism: OK
   use don’t care (or probability distribution) as output observation

4. Observable implementation nondeterminism: AVOID
   e.g. multi-threaded systems, scheduled systems
What is an Observation?

Traditional software: input and output values

0 → D → 1

0 → ND → 0 or 1
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0 → $D$ → 1

0 → $ND$ → 0 or 1

0 → $\bot$
What is an Observation?

Traditional software: input and output values

0 \rightarrow D \rightarrow 1 \quad 0 \rightarrow ND \rightarrow 0 \text{ or } 1

0 \rightarrow \bot

Real-time software: input and output values and times

(0, t) \rightarrow D \rightarrow (1, t+0.5) \quad (0,t) \rightarrow ND \rightarrow (1, t+0.5) \text{ or } (1, t+1)
What is an Observation?

Traditional software: input and output values

- $0 \rightarrow \text{D} \rightarrow 1$
- $0 \rightarrow \text{ND} \rightarrow 0$ or $1$
- $0 \rightarrow \bot$

Real-time software: input and output values and times

- $(0, t) \rightarrow \text{D} \rightarrow (1, t+0.5)$
- $(0, t) \rightarrow \text{ND} \rightarrow (1, t+0.5)$ or $(1, t+1)$
- $(0, t) \rightarrow \bot \rightarrow (1, [t+0.5, t+1])$
What is an Observation?

Traditional software: input and output values

0 → D → 1

0 → ND → 0 or 1

Reliable software: output probabilities

0 → D → Pr(0) = 0.1
Pr(1) = 0.9

0 → ND → ⊥

Pr(0) = 0.1
Pr(1) = 0.9

or

Pr(0) = 0.2
Pr(1) = 0.8
Giotto Project: Deterministic Real Time

Can we build a real-time programming language that treats time in the way in which high-level languages treat memory?

- programmer specifies the time of outputs
- programmer assumes the platform offers sufficient performance
- compiler generates a suitable schedule or throws an exception
LET (Logical Execution Time) Programming Model

read sensor input at time $t$

write actuator output at time $t+d$, for specified $d$
Compiler reconciles Logical and Physical Execution Times
Time and Value Determinism

- Timing predictability: minimal jitter
- Value predictability: no data races
Contrast LET with Scheduled Programming Model

make output available as soon as ready
Contrast LET with Scheduled Programming Model

Task output values depend on which task finishes first!
Can we build a programming language that treats reliability in the way in which high-level languages treat memory?

- programmer specifies the long-run failure rate of outputs
- programmer assumes the platform offers sufficient reliability
- compiler generates a task replication mapping or rejects the program
Program:
write actuator y every 4 ms with failure rate $\leq 0.001$;

LOGICAL RELIABILITY
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LOGICAL RELIABILITY

Platform:
CPU reliability 0.97;
sensor reliability 0.95;

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LOGICAL RELIABILITY

Platform:
CPU reliability 0.97;
sensor reliability 0.95;

PHYSICAL RELIABILITY

Compiler replicates computation of actuator value on 2 CPUs:
$(1 - 0.97)^2 \leq 0.001$
Challenge 2:
Build Robust Systems
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Robust = Continuous

A system is continuous if for all real-valued quantities, small input changes cannot cause large output changes.
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Build Robust Systems

Robust = Continuous

A system is *continuous* if for all real-valued quantities, small input changes cannot cause large output changes.

-∀ ε>0. ∃ δ>0. input-change ≤ δ ⇒ output-change ≤ ε

-can apply only to real-valued quantities: sensor readings and actuator settings; time stamps; probabilities
In general programs are not continuous. But they can be more continuous:

read sensor value x at time t;
compute “continuous” function y = f(x);
write output value y at time t+d;

Or less continuous:

read sensor value x;
if x \leq c \text{ then } y = f_1(x)
else y = f_2(x);
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Or less continuous: Better:

read sensor value $x$;
if $x \leq c$ then $y = f_1(x)$
else $y = f_2(x)$;

if $x \leq c - \varepsilon$ then $y = f_1(x)$;
if $x \geq c + \varepsilon$ then $y = f_2(x)$
else $y = \frac{f_1(x) + f_2(x)}{2}$;
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else $y = (f_1(x) + f_2(x))/2$;

We need system preference metrics in addition to boolean correctness criteria.
What is an Observation?

Traditional software:

\[
\begin{align*}
0 & \rightarrow \text{NC} & 1 \\
1 & \rightarrow 0 \\
\end{align*}
\]

Sensor software:

\[
\begin{align*}
x \in \mathbb{R} & \rightarrow C & f(x) \in \mathbb{R} \\
\end{align*}
\]
What is an Observation?

Traditional software:

Sensor software:

Real-time software:
Topology on Observations

Real time:

![Diagram showing signals and the Skorohod metric](image)

e.g. Skorohod metric on signals
Topology on Observations

Real time:

Reliability:

sensor value validity 0.99  \rightarrow \text{C}  \rightarrow \text{actuator value validity 0.95}

e.g. Skorohod metric on signals
Conclusion

Topology of observations $T$ should be an essential part of every system specification:

1. Determinism of a model depends on $T$.
2. Continuity of a model depends on $T$.

Different choices of $T$ will lead to different designs.
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Topology of observations $T$ should be an essential part of every system specification:

1. Determinism of a model depends on $T$.
2. Continuity of a model depends on $T$.

Different choices of $T$ will lead to different designs.

The choice of modeling language should depend on the choice of $T$.

**Research Challenge:** For given $T$, we need languages that guarantee determinism and continuity.