Verification of Embedded Software
from Mars to Actions

Charles Pecheur, UC Louvain
(formerly RIACS / NASA Ames)


From Mars ...

... to Actions

```
MODULE agent
  IVAR move : boolean;
  VAR count : 0..10;
  ASSIGN
    init(count) := 0 ;
    next(count) := case
                     move & count < 10: count + 1;
                     1 : count;
                   esac;
  DEFINE win := (count=10);

MODULE main
  VAR alice : agent;
  VAR bob : agent;

SPEC !EAX (bob.move) bob.count = 0
SPEC AAX (bob.move & alice.move) (bob.count > 0 & alice.count > 0)
SPEC AAF (bob.move) bob.win
```

Outline

Model-Based Autonomy and Diagnosis

Verification of Model-Based Controllers

Verification of Diagnosability

Symbolic Verification with Knowledge

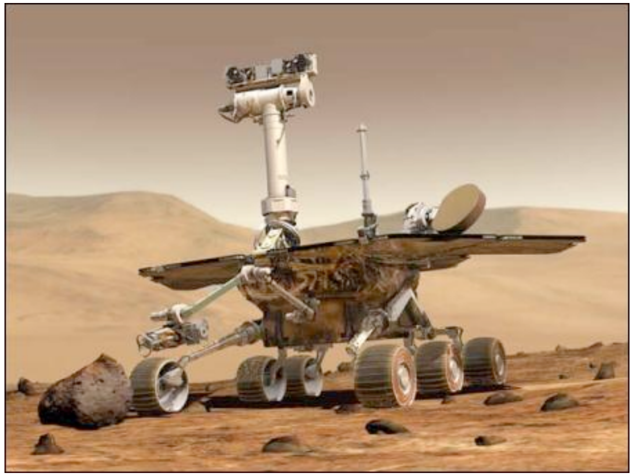
Symbolic Verification with Actions

Conclusions

Autonomy (at NASA)

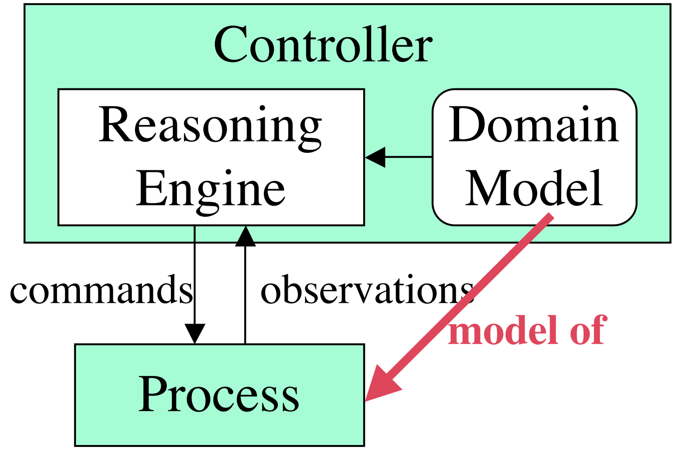
Autonomous spacecraft = on-board intelligence (= AI)

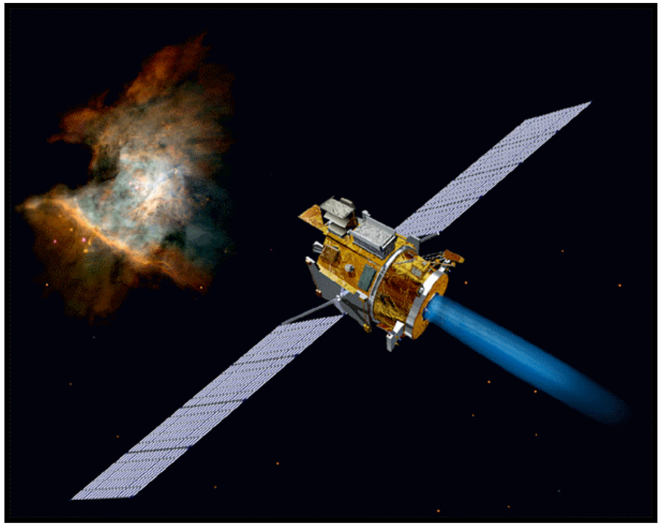
- **Goal:** Unattended operation in an unpredictable environment
- **Approach:** **model-based reasoning**
- **Pros**: smaller mission control crews, no communication delays/blackouts
- **Cons:** **Verification and Validation ???** Much more complex, huge state space
- Better verification is critical for adoption



Model-Based Autonomy

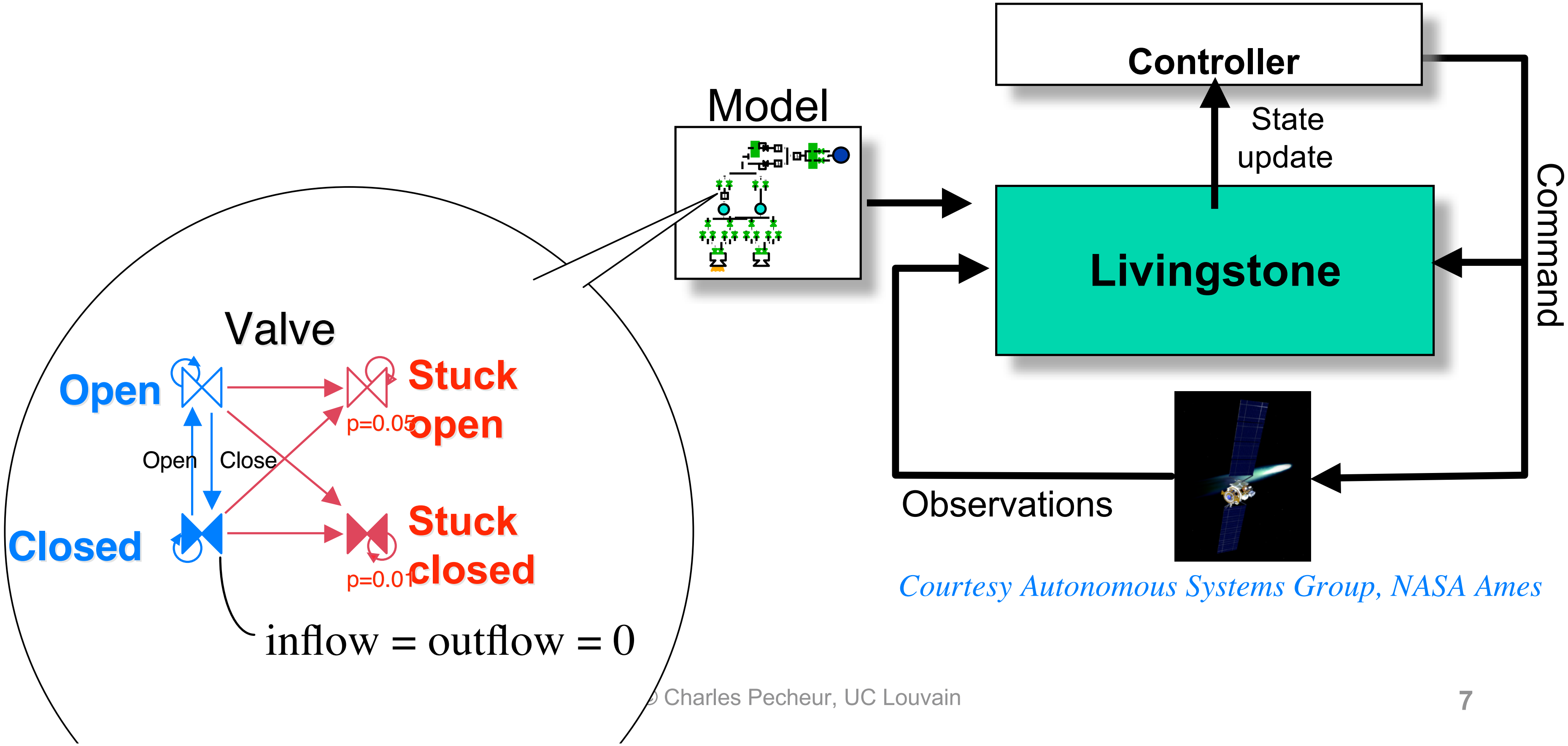
- Based on AI technology
- Generic **reasoning engine**
  + application-specific **model**
- Model describes (normal and faulty) behaviour of the process
- Engine selects control actions "on-the-fly" based on the model
  - ... rather than pre-coded decision rules
  - better able to respond to unanticipated situations





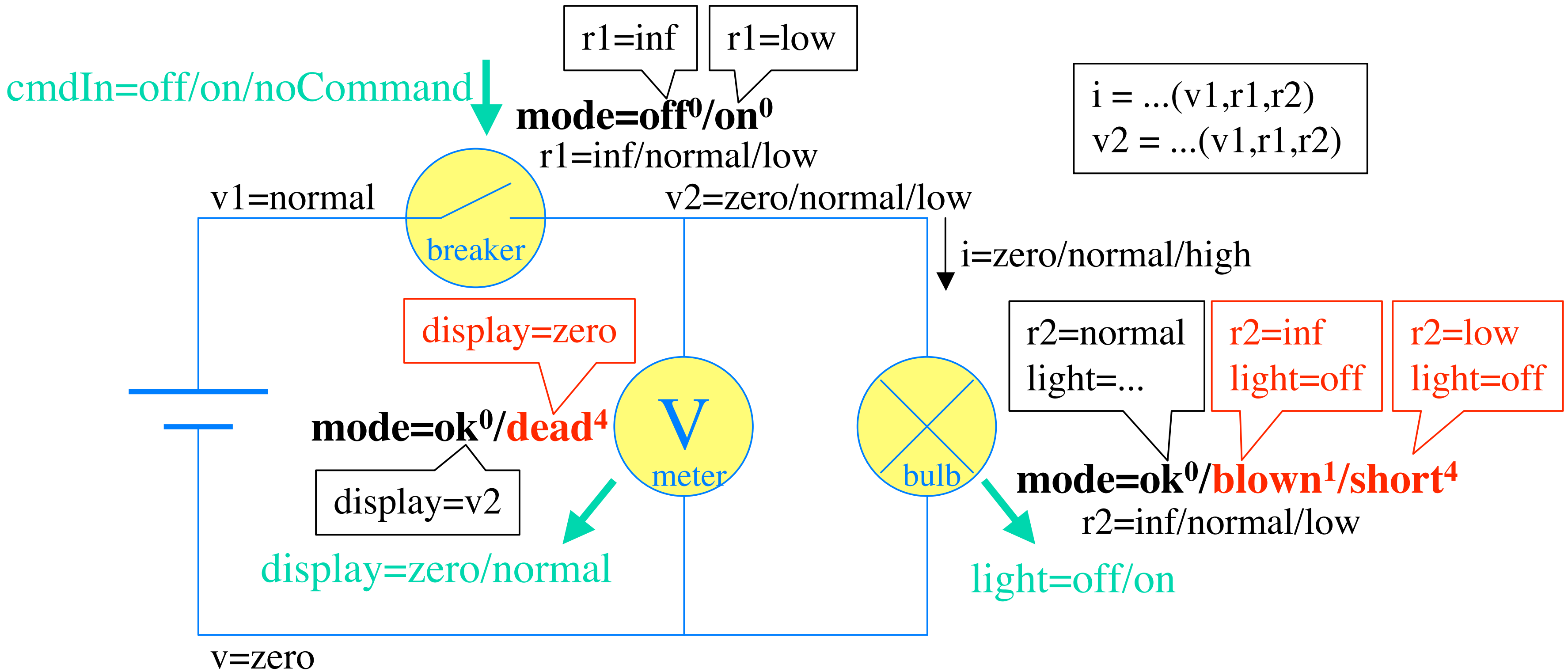
Livingstone

- Model-based diagnosis system from NASA Ames
  - i.e. an advanced state estimator
- Uses a discrete, qualitative model to reason about faults
  => naturally amenable to formal analysis



Courtesy Autonomous Systems Group, NASA Ames

A Simple Livingstone Model



Goal: determine **modes** from observations
Generates and tracks *candidates*

breaker	bulb	meter	rank
off^0	**ok^0**	**ok^0**	**0**
off^0	**ok^0**	**blown^1**	**1**
on^0	**dead^4**	**short^4**	**8**

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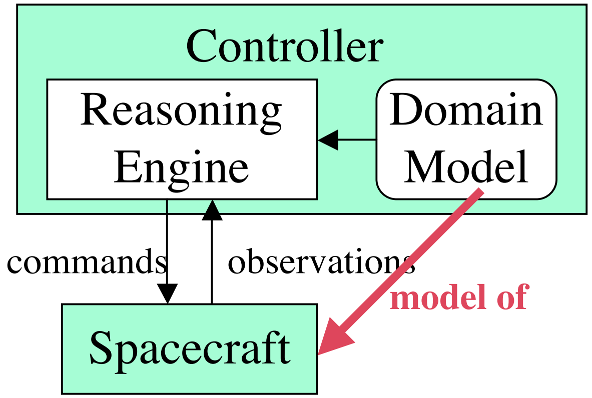
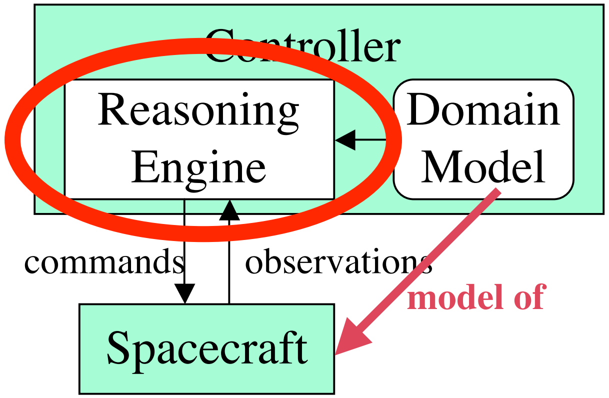
Verify Model-Based Control?



Of course, but what exactly?

- The model?
- The engine?
- The whole controller?
- **All of the above!**

Verification of the Engine

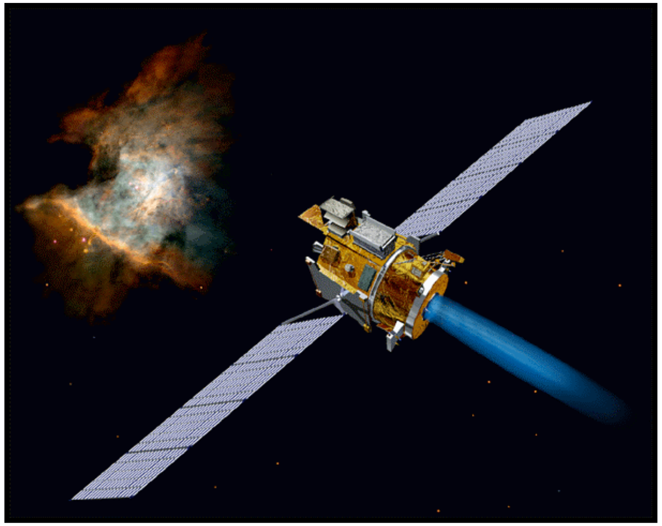


- A (technically complex) computer program
  - Use traditional software verification approaches
  - Maybe full-blown proof on core algorithms
- Generic, re-used across applications
  - More likely to be stable and trustable
  - Like compilers, interpreters, virtual machines, etc

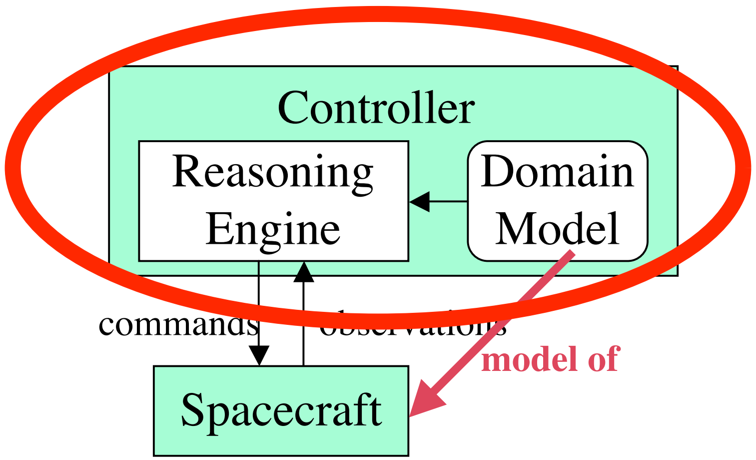
The RAX Bug

Remote Agent Experiment (1999)

- **cause** : missing critical section in concurrent program
- **effect** : race condition and deadlock in flight
  - in supervised experiment, no mission damage
- **solution** : model checking
  - a similar bug was found before flight using SPIN on another part of the code
  - See [Havelund et al. 2000]



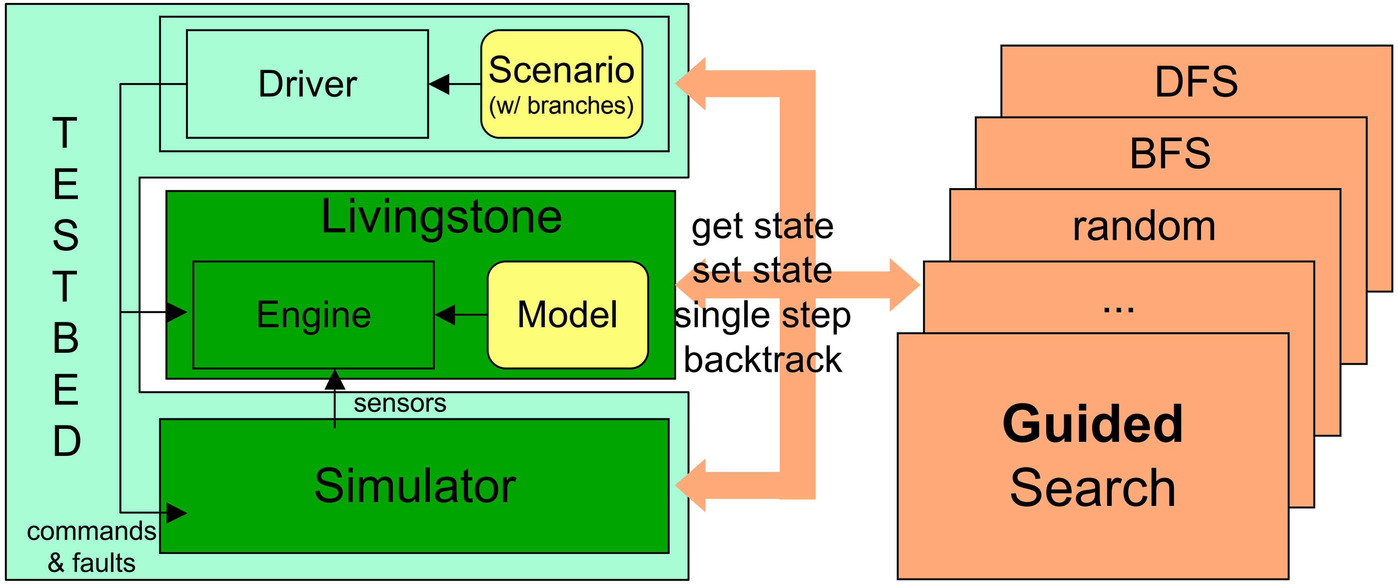
Verification of the Controller



- good model + good engine ≠> good controller
  - Heuristics in engine, simplifications in model
- System-level verification
  - Controller as black (or grey) box
  - Need a model of the environment (test harness)
  - Applicable to others than model-based

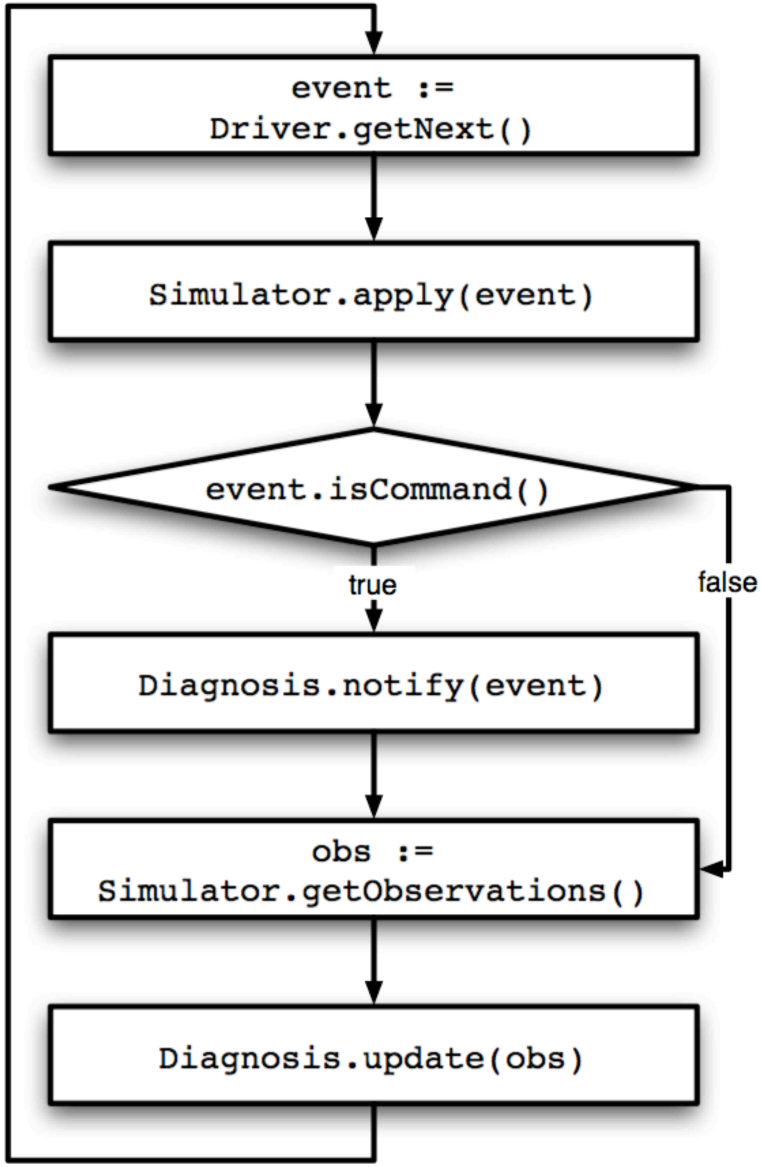
Livingstone PathFinder

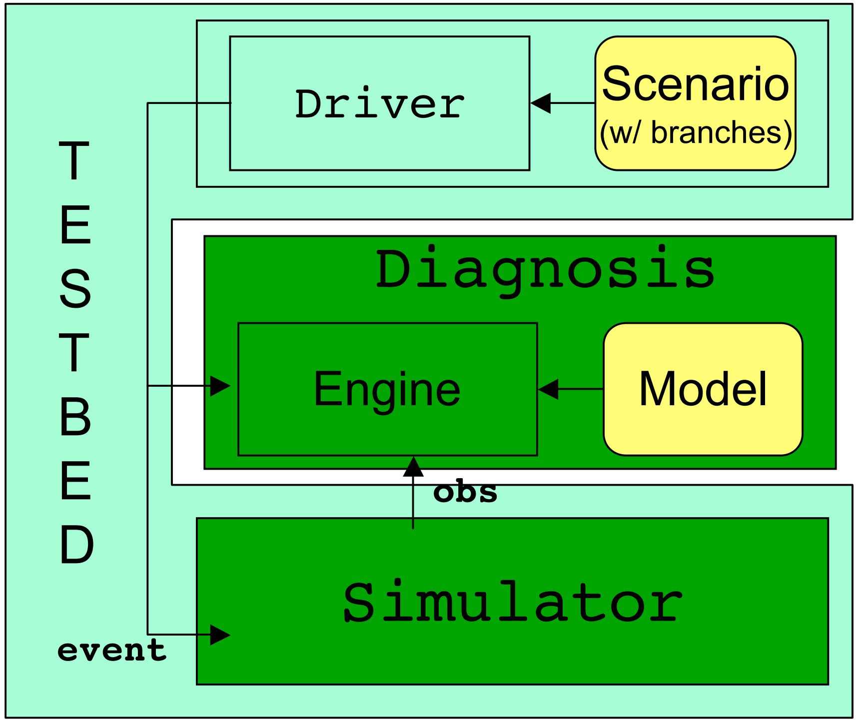
with Tony Lindsey (QSS / NASA Ames)



- An advanced testing/simulation framework for Livingstone applications
  - Executes the **Real Livingstone Program** in a simulated environment (testbed)
  - **Instrument** the code to be able to **backtrack** between alternate paths
- **Modular** architecture with generic APIs (in Java)
  - allows different diagnosers, simulators, search algorithms and strategies, error conditions, ...
- See TACAS'04 paper

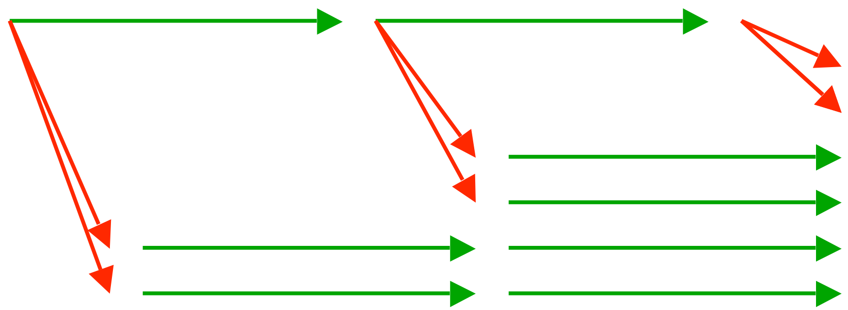
One Diagnosis Step





LPF Scenario Example

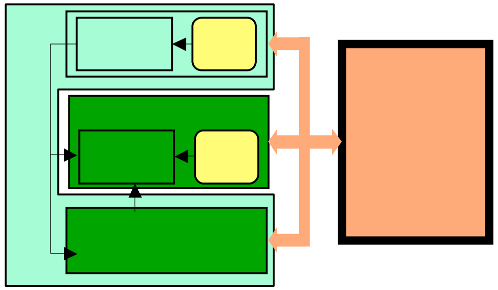
```
mix {
   "command test.sv02.valveCmdIn=close";
   "command test.sv02.valveCmdIn=open";
   ...
} and {
   choose
      "fault test.forwardLO2.mode=unknownFault"; or
      "fault test.mpre101p.mode=faulty"; or
      ...
}
```



- Sequence of commands || choice of faults
- "default" scenario, can be generated automatically

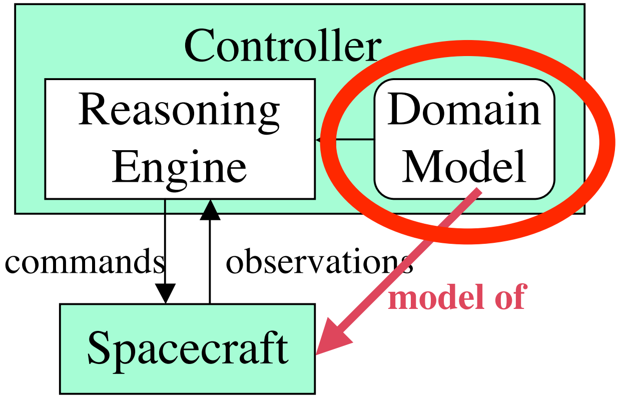
LPF Search

- The whole testbed is seen as a transition system
- API to enumerate transitions, backtrack, get/set state
  - Shared with Java PathFinder (v.2)[Visser et al. 00]
  - Principle inspired from OPEN/CAESAR[Garavel 98]
- Search engine fixes exploration strategy
  - Depth-First
  - Breadth-First
  - **Heuristic**
  - Others are possible (random, pattern-based, interactive)



- + Halting conditions (for any strategy)
  - Find first / all / shortest error trace(s)

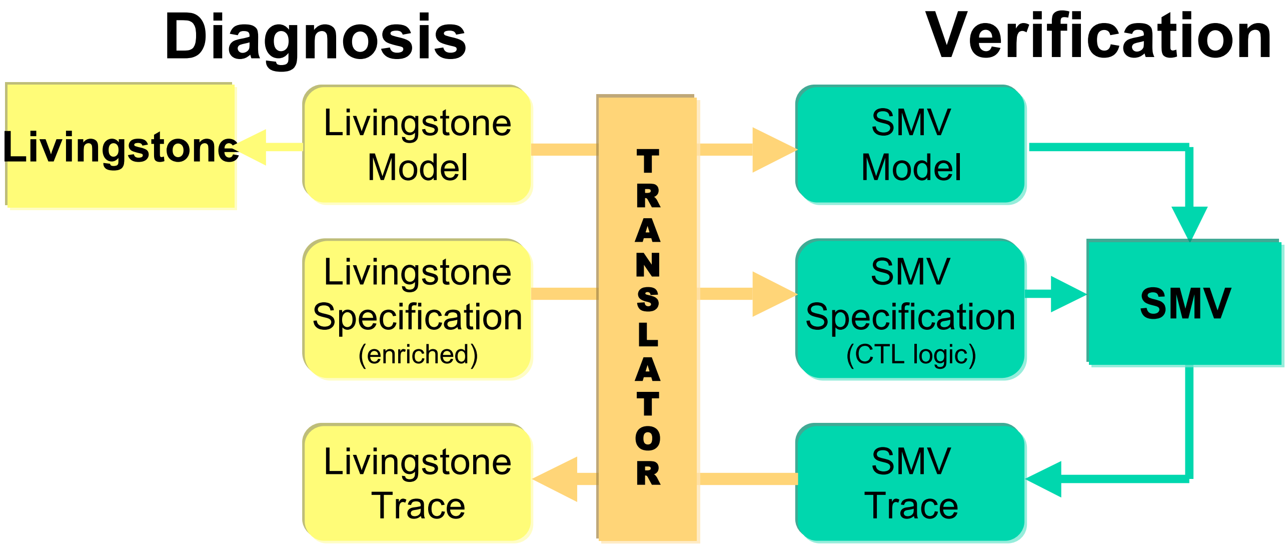
Verification of the Model



- This is the "application code"
  - where the development effort (and bugs) are
- Abstract, concise, amenable to formal analysis
  - this is another benefit of model-based approaches
  - ... or model-based design in general
- Use **symbolic model checking**

Livingstone-to-SMV Translator

Joint work with Reid Simmons (Carnegie Mellon)



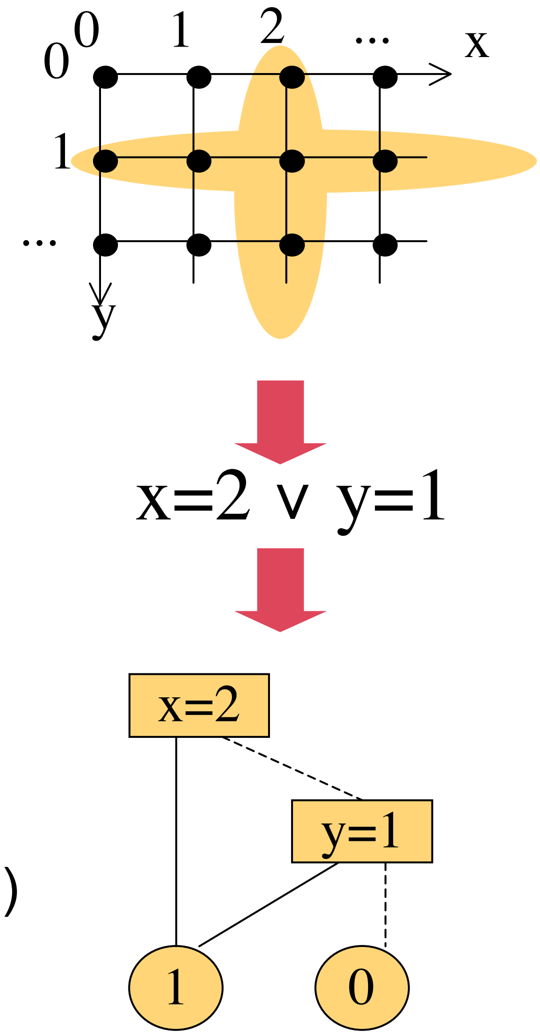
- A translator that converts Livingstone models, specs, traces to/from SMV (in Java)
  - SMV: symbolic model checker (both BDD and SAT-based) allows exhaustive analysis of very large state spaces (10^{50+})
- Hides away SMV, offers a **model checker for Livingstone**
- Enriched specification syntax (vs. SMV's core temporal logic)
- Graphical interface, integration in Livingstone development tools

SMV / NuSMV

Mainstream **symbolic** model checker

– Original SMV from Carnegie Mellon, currently NuSMV from IRST (and Cadence SMV)

- Rich modeling **language**
- Many **features and options**
- Uses **symbolic** computation over **boolean** encoding
  – using BDDs or SAT (bounded)
  – finite models
  – Can handle very large state spaces (10^{50+})

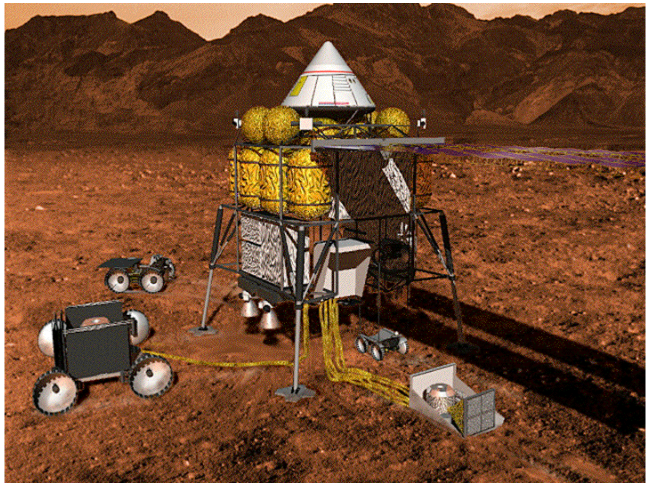


In-Situ Propellant Production

- Use atmosphere from Mars to make fuel for return flight.
- Livingstone controller developed at NASA KSC.
- Components are tanks, reactors, valves, sensors...
- Exposed improper flow modeling.
- Latest model is 10^{50} states.

$$CO_2 + 2H_2 \longrightarrow CH_4 + O_2$$

Mars atmosphere (CO_2), on-board ($2H_2$), fuel (CH_4), oxidizer (O_2)



Verification of Diagnosis Models

- Coding Errors
  - e.g. Consistency, well-defined transitions, ...
  - Generic
  - Compare to Lint for C
- Model Correctness
  - Expected properties of modeled system
  - e.g. flow conservation, operational scenarios, ...
  - Application-specific
- **<u>Diagnosability</u>**
  - Are faults detectable/diagnosable?
    - Given available sensors
    - In all/specific operational situations (dynamic)

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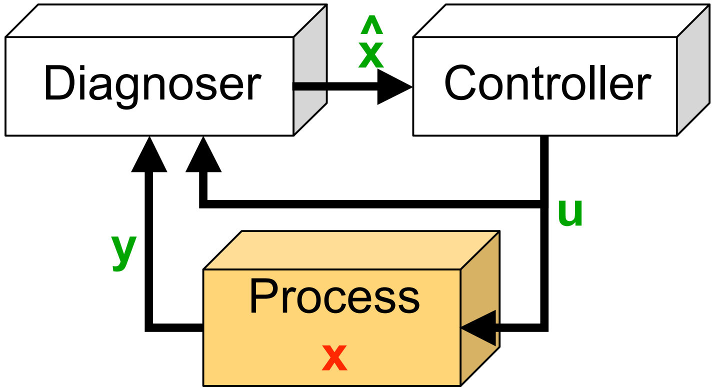
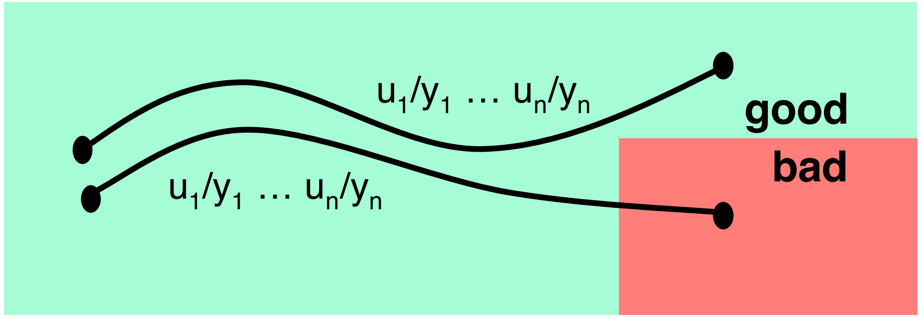
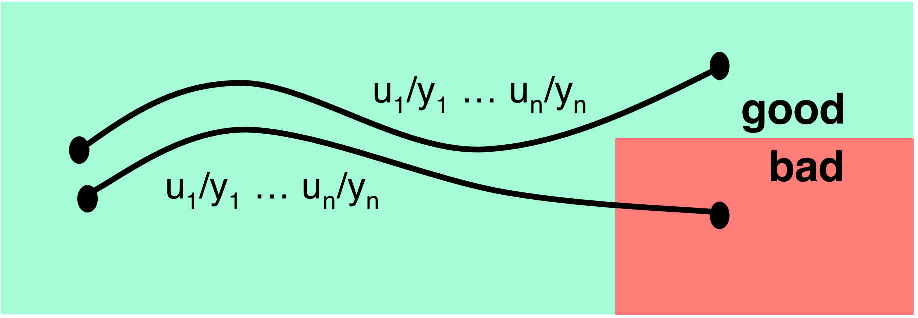
Diagnosability

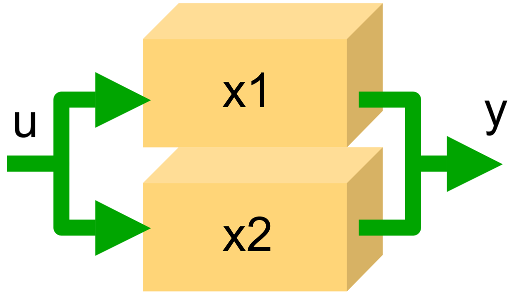




- **Diagnosis:** estimate the hidden state **x** (incl. failures) given observable commands **u** and sensors **y**.
- **Diagnosability**: Can (a smart enough) *Diagnoser* always tell when *Process* comes to a **bad** state?
- **Property of the Process** (not the Diagnoser)
  - even for non-model-based diagnosers
  - but analysis needs a (process) model

Verification of Diagnosability



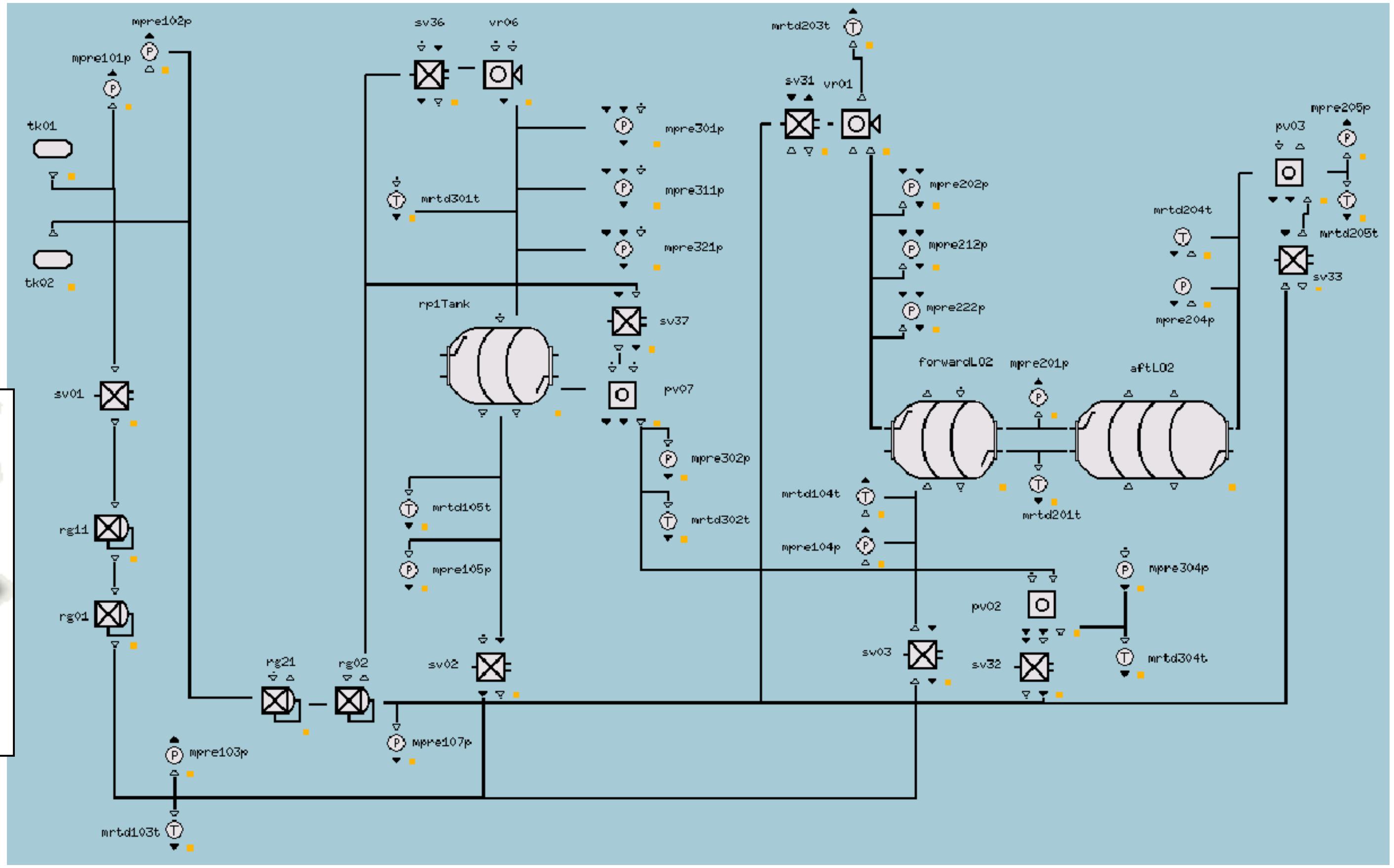


- **Intuition**: **bad** is diagnosable if and only if there is no pair of trajectories, one reaching a **bad** state, the other reaching a **good** state, with identical observations.
  - or some generalization of that: (context, two different faults, ...)
- **Principle**:
  - consider two concurrent copies *x1*, *x2* of the process, with coupled inputs *u* and outputs *y*
  - check for reachability of (good(x1) && bad(x2))
- Back to a classical (symbolic) model checking problem !
- Supported by Livingstone-to-SMV translator

Université catholique de Louvain INGI

X-34 / PITEX

- Propulsion IVHM Technology Experiment (ARC, GRC)
- Livingstone applied to propulsion feed system of space vehicle
- Livingstone model is $4 \cdot 10^{33}$ states



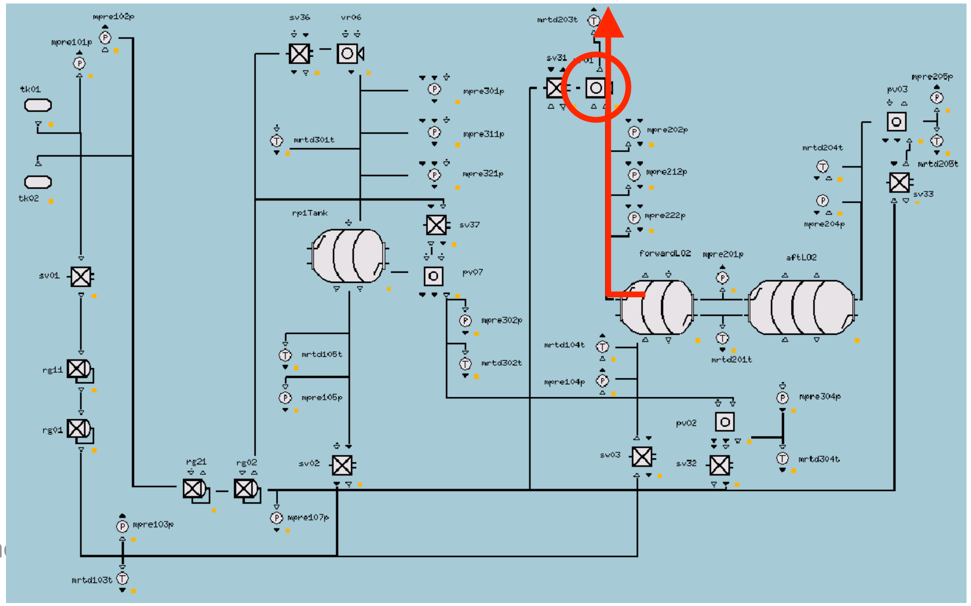
PITEX Diagnosability Error

with Roberto Cavada (IRST, NuSMV developer)

- *"Diagnosis can decide whether the venting valve VR01 is closed or stuck open (assuming no other failures)"*

  INVAR !test.multibroken() & twin(!test.broken())
  VERIFY INVARIANT !(test.vr01.mode=stuckOpen &
  twin(test.vr01.valvePosition=closed))

- Results show a pair of traces with same observations, one leading to **VR01 stuck open**, the other to **VR01 closed**. Application specialists fixed their model.



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Epistemic Logic

- Reasoning about knowledge

  K_a φ = agent *a* **knows** φ

- Interpreted over an **Interpreted System (IS)**
  - **Transition system** T +
  - **Observation functions** $obs_a(\sigma)$ over runs σ of T
  - K_a φ holds after σ iff
    φ holds after all σ' such that $obs_a(\sigma) = obs_a(\sigma')$
- **CTLK** = temporal + epistemic logic

Observation Function

- **In general** : agents reason about "everything they have seen so far" (total recall)
  - $obs_a(\sigma)$ over **runs** σ
  - memory built into the logic
  - model checking hard to undecidable
- **Observational view** : agents reason about the current state only
  - $obs_a(s)$ over **states** s
  - memory explicit in the model
  - symbolic model checking can be generalized from CTL to CTLK

Diagnosability and CTLK

joint work with Franco Raimondi (UC London)

Considering the diagnoser as an agent *D* observing the system,

Fault *F* is diagnosable

iff

$AG\ (K_D F \vee K_D \sim F)$

- **Diagnosability** can be framed as a **temporal epistemic** model-checking problem
- Caveat : general diagnosability requires total recall
  - or explicit (bounded) memory of observations

From CMAS to SMV

- CMAS : symbolic model checker for CTLK
  - developed by Franco Raimondi
  - BDD-based
  - Good performance but very crude modelling language
- Could we do CTLK in NuSMV?
  - Leverage SMV's rich modelling language
  - Re-use models generated from Livingstone
- Need a reduction from CTLK to (enhanced?) CTL

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From Knowledge to Actions

- The observation function $obs_a(s)$ induces an **accessibility** (equivalence) **relation** $\sim_a$ over reachable states s

$$s \sim_a s' \text{ iff } obs_a(s) = obs_a(s')$$

- An **interpreted system** is a Kripke structure with several transition relations $\rightarrow, \sim_{a1}, \ldots, \sim_{an}$
- Or equivalently, a **labelled transition system** (LTS) over an action alphabet {t, a1, ..., an}
- **Corresponding reduction of CTLK?**

Action-Based Logics

- Large body of published work in **action-based temporal logics** (applicable to LTS)
  - ACTL [deNicola-Vaandrager], ACTL*,Hennessy-Milner, etc.
  - Do not quite fit our purpose
  - No (well-known?) symbolic model-checker

Action-Restricted CTL (ARCTL)

- Variant of ACTL
- Action conditions α on path quantifiers

  e.g. $\mathbf{A}_\alpha\mathbf{F}\ \varphi$ = on all α-paths, sooner or later φ

  – vs. on temporal quantifiers in ACTL

  e.g. $\mathbf{AF}_\alpha\ \varphi$ = on all paths, there is an α-prefix to φ
- α-restricted formula on full model = unrestricted formula on α-restricted model
- (IS sat CTLK) can be reduced to (LTS sat ARCTL)
  – needs reachability = reverse temporal transitions

Symbolic Model-Checking for Action-Based Logics

- Classical symbolic model-checking for CTL generalizes naturally to ARCTL or ACTL
  - some subtleties due to finite α-paths and fairness

$$
\begin{aligned}
eax(A,S) &= \{s \mid \exists a, s' \cdot s \xrightarrow{a} s' \wedge a \in A \wedge s' \in S\} \\
eau(A,S,S') &= \mu Z \cdot S' \cup (S \cap eax(A,Z)) \\
eag(A,S) &= \nu Z \cdot S \cap eax(A,Z)
\end{aligned}
$$

- NuSMV already has “actions” in models
  - called input variables (IVARs)
  - but not allowed in CTL

Action-Based Logics in NuSMV

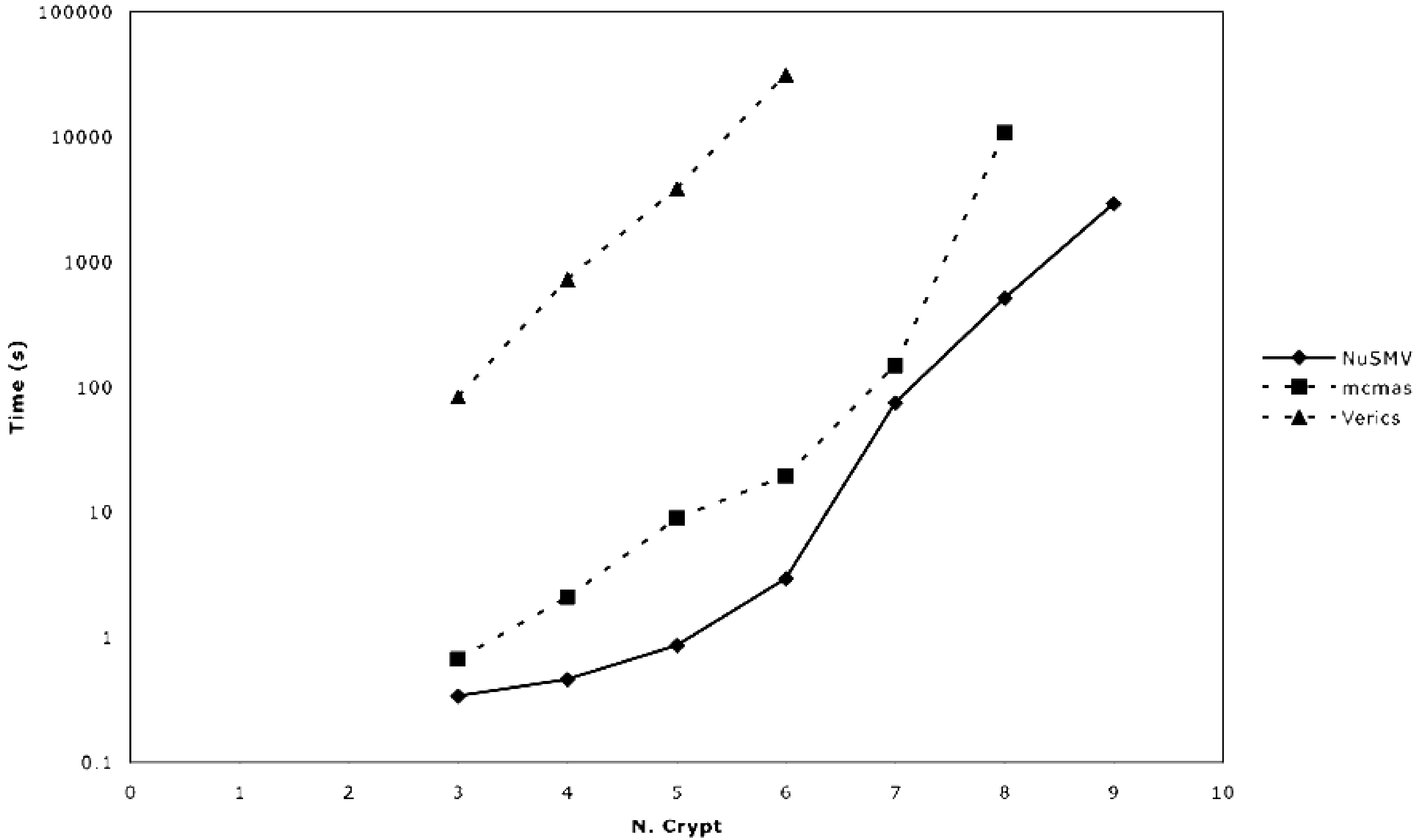
We added ARCTL support to NuSMV

- V1: reduction to KS + CTL,
  projecting actions into post-states
  e.g. $\mathbf{A}_\alpha\mathbf{X}\ \varphi$ reduces to $\mathbf{AX}\ (\alpha \Rightarrow \varphi)\ \land\ \mathbf{EX}\ \alpha$
- V2: native ARCTL support, using IVARs
- see [Pecheur-Raimondi 2006]

CTLK in NuSMV

- CTLK and agents (observed variables) handled by a macro package (m4)
- Good performance wrt. dedicated model checkers (CMAS, Verics), see next slide
- see [Raimondi-Pecheur-Lomuscio 2005]

CTLK on Dining Cryptographers



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Summary: From Mars to Actions

Deep-space missions (incl. **Mars**)

=> Model-based autonomy (incl. diagnosis)

=> **Model-based verification**

=> **Diagnosability**

=> **Epistemic Logics**

=> **Logics with Actions**

Lessons Learned

- Verification of **model-based controllers**
  - **Needs** advanced verification (because of large state space)
  - **Facilitates** advanced verification (thanks to model)
- Verification of **control software**
  - Control loop, observability/commandability
    - In particular, failure diagnosability and recoverability
  - Leads to epistemic, action logics
- **Model checking**
  - Applicable to these problems
  - symbolic model checking saves the day
- Verification of **software**
  - All other principles still apply: process, testing, ...

Perspectives

- Key ideas:
  - **model-based analysis (model checking)**
  - **partial observability**
- Extensions
  - from discrete to continuous, real-time, **hybrid models**
  - from fault diagnosis to **planning**
    - e.g. test-case generation for planners
      see [Raimondi-Pecheur-Brat 2007]
- Connections
  - with classical **risk analysis** (fault trees, FMEA)
  - with **man-machine interface** issues (observability!)
  - with **game theory** (the Controller vs. the Environment)

Thank you!

Publications vailable at
http://www.info.ucl.ac.be/~pecheur/publi/

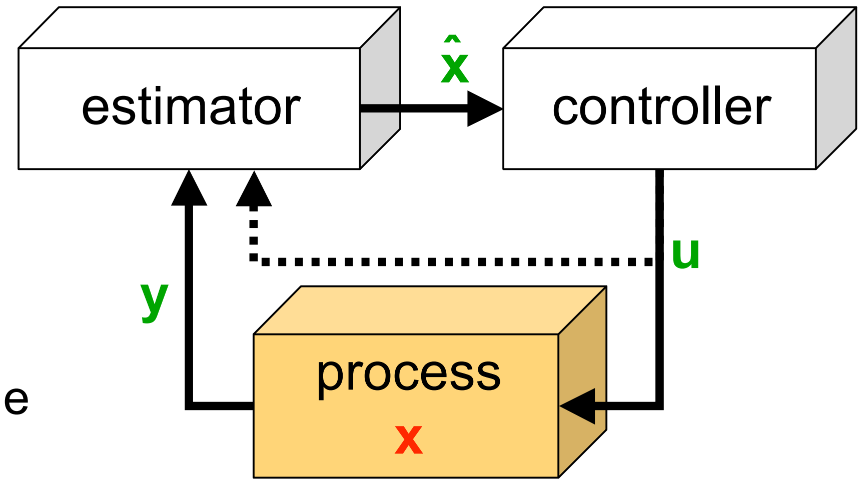
Backup Slides

Process Control

- Partially observable process (hidden state x, estimated by $\hat{x}$)

- **observability** :
  infer x from y (and u)
- **commandability** :
  impose x through u

- **control theory** :
  x = physical quantities, differentiable
  → linear models, PDI controllers
- **logic processes** :
  x = states, modes, **failures**, discrete
  → state machines, programmable automata



Verification of Control Systems

- Monitors and commands a process
  - in particular, failure diagnosis and recovery
- Complex
  - multiple controllers, asynchronism, coupling
  - race conditions, feature interaction
- Software
  - powerful and flexible but not linear, not continuous
- **How to Validate ?**
  - including "diagnosability" and "recoverability" from failures ?

Temporal Epistemic Logic

- Reasoning about time and knowledge: **CTLK** logic

φ	::=	$p \mid \neg\varphi \mid \varphi\wedge\varphi$	*atomic propositions, boolean ops*
	$\mid$	$EX\ \varphi \mid E[\varphi\ U\ \varphi] \mid EG\ \varphi$	*temporal ops*
	$\mid$	$K_a\ \varphi \mid E_G\ \varphi \mid D_G\ \varphi \mid C_G\ \varphi$	*knowledge ops*

  with $\varphi\vee\varphi' := \neg(\neg\varphi\wedge\neg\varphi')$, $EF\ \varphi := E[true\ U\ \varphi]$, $AG\ \varphi := \neg EF\ \neg\varphi$, ...

- Interpreted over an *Interpreted System* =
  - *Transition system* (Kripke structure) T +
  - *Observation functions* $obs_a(\sigma)$ over runs σ of T, for each agent a

$$\sigma \sim_a \sigma' \quad \text{iff} \quad obs_a(\sigma)=obs_a(\sigma')$$

$$\sigma \models K_a\ \varphi \quad \text{iff} \quad \text{for all } \underline{\text{reachable}}\ \sigma'\ .\ \sigma\sim_a\sigma' \Rightarrow \sigma' \models \varphi$$

CTLK + correctness

$K^{\wedge}{}_a^G\ \varphi$ = a knows φ, assuming everyone in G "works correctly"

- "works correctly" is a state condition
- Useful for diagnosis: one agent per component, works correctly iff non-fault mode
- Verification supported by Raimondi's tool (BDD based)
- Expressivity issue: correctness in present state vs. in future
- Work in progress!

TO DO

- Full content
- Add references
  - Diagnosability
  - MC of CTLK
  - MC of Actions