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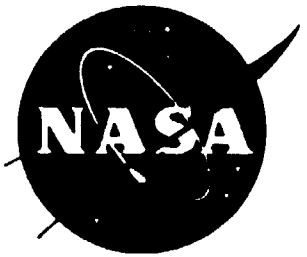

Verification and Validation of Model-Based Autonomous Systems

Charles Pecheur, RIACS (ARC)

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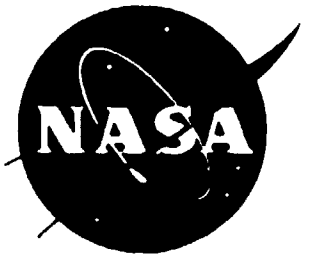
Project Profile



- 3-year project, FY99 to FY01
- Performed by ARC,
  With grant to CMU (Reid Simmons),
  Delivered to KSC.
- Goal: support V&V of Livingstone-based applications by the application developers (not by V&V experts)
- Two complementary approaches:
  - Symbolic model checking of *models*
  - Closed-loop verification of *applications*

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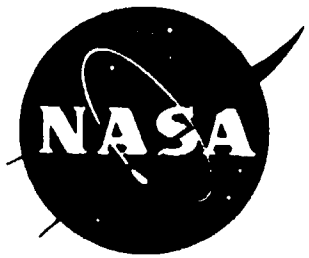
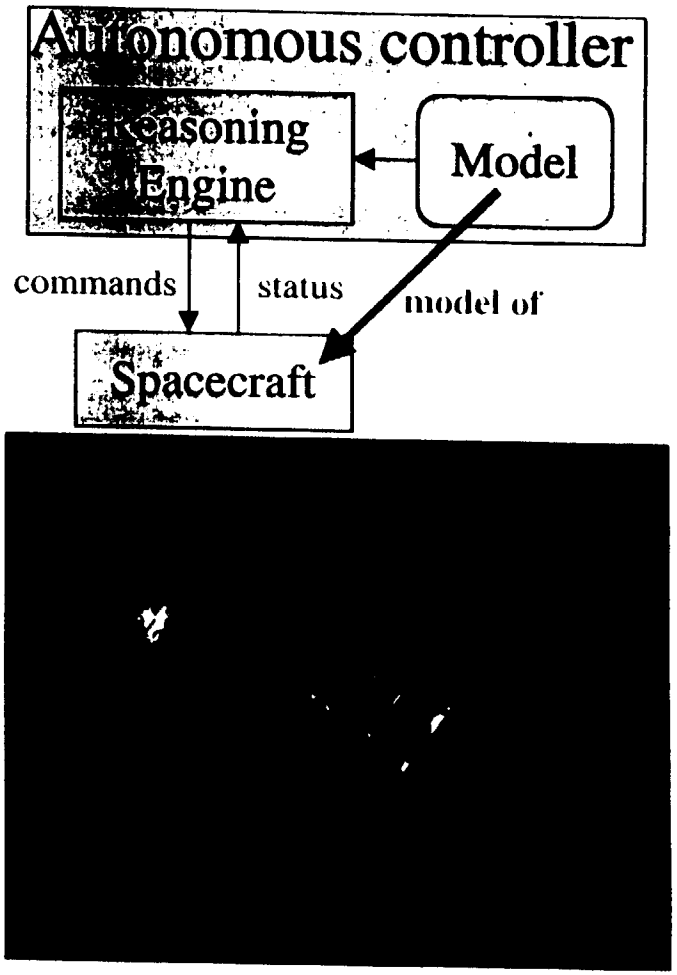
Model-Based Autonomy



- Based on AI technology
- General reasoning engine + application-specific model
- Use model to respond to unanticipated situations



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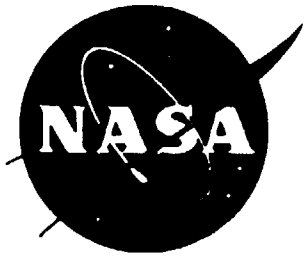
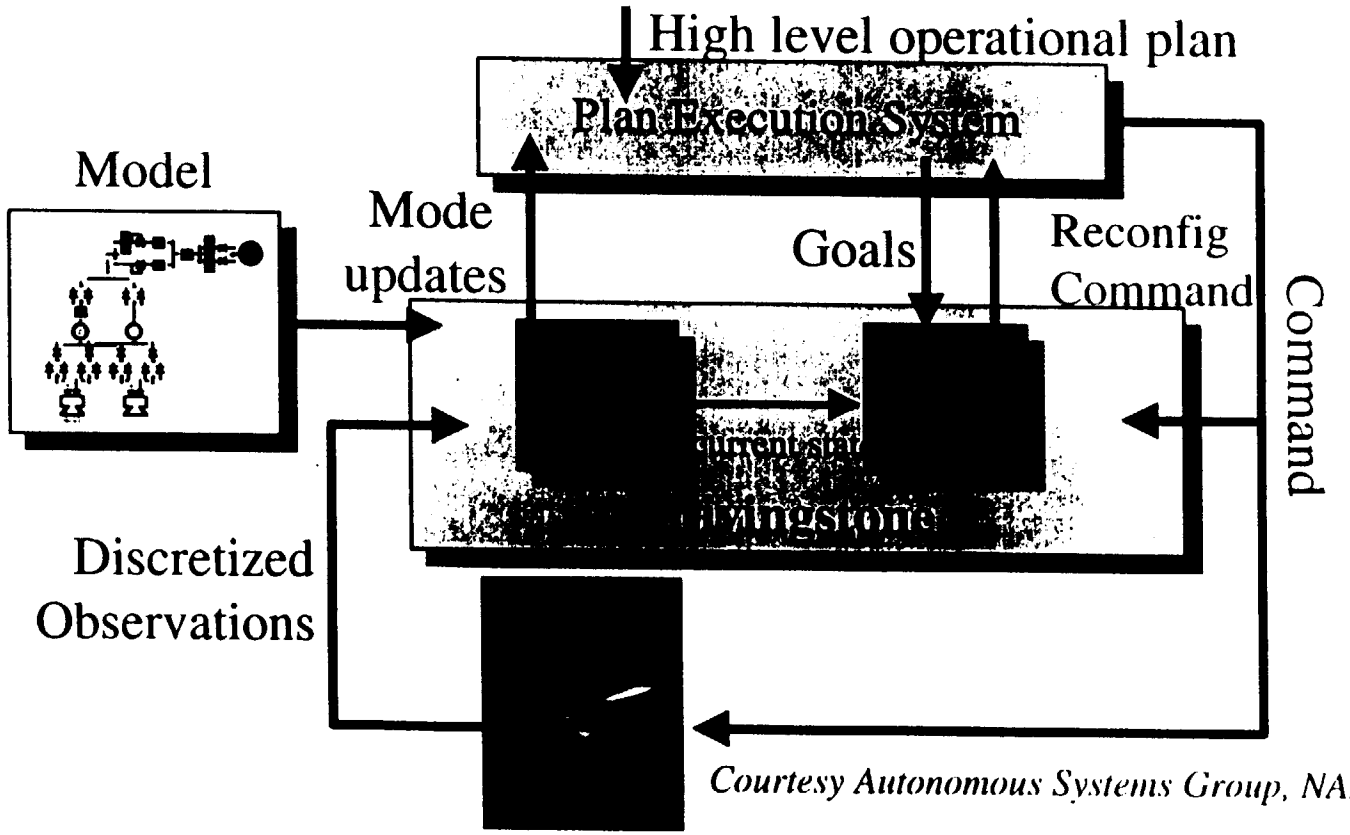
The Livingstone MIR



Remote Agent's model-based fault recovery sub-system



Courtesy Autonomous Systems Group, NASA Ames

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MPL2SMV

NASA

Autonomy

Livingstone

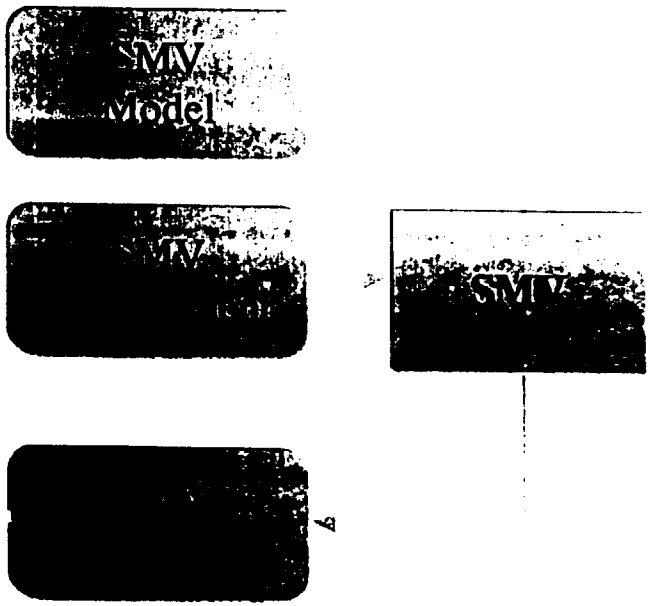
Livingstone Model

Livingstone Requirement

Livingstone Trace

MPL2SMV

Verification



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Livingstone to SMV Translation

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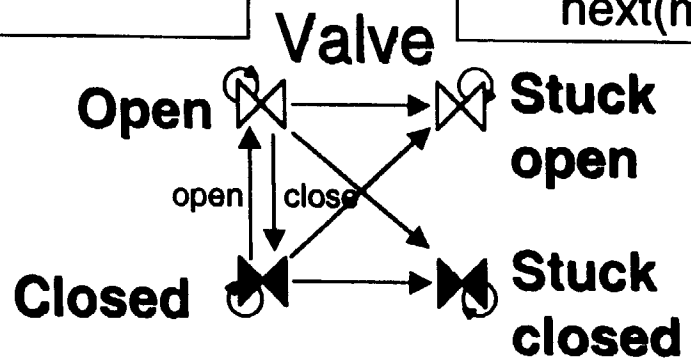
NASA

Livingstone Model

```
(defcomponent valve ()
  (:inputs (cmd :type valve-cmd))
 ...
  (Closed :type ok-mode
    :transitions
      ((do-open :when (open cmd)
        :next Open) ...))
  (StuckC :type :fault-mode ...)
 ...)
```

SMV Model

```
MODULE valve
VAR     mode: {Open,Closed,
                StuckO,StuckC};
        cmd: {open,close};
DEFINE faults:={StuckO,StuckC};
TRANS
  (mode=Closed & cmd=open) ->
    (next(mode)=Open |
      next(mode) in faults)
```



Livingstone Autonomous Controller

SMV Symbolic Model Checker

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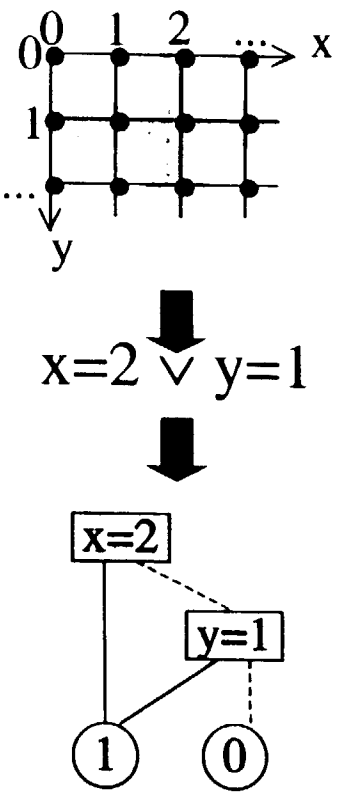
Symbolic Model Checking

- Manipulates sets of states,
  Represented as boolean formulas,
  Encoded as binary decision diagrams.
- Can handle larger state spaces (10^{50} and up).
- BDD computations:
  - Good in average but exponential in worst case.
  - Computation time depends on BDD size
    => number of variables, complexity of formulas,
    but not directly state space size.
- Example: SMV (Carnegie Mellon U.)



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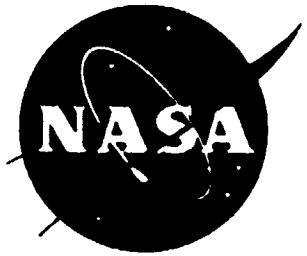
From Livingstone Models to SMV Models



- Co-developed with CMU
- Based on Livingstone 1 (Lisp)
- 4K lines of Lisp
- Similar nature => translation is easy
- Properties in temporal logic + pre-defined patterns
- Temporal queries
  - e.g. "what faults imply eventual recovery"
  - Proof-of-concept prototype (done at CMU)
  - deceptive results so far
- Migration to Livingstone 2 (in progress)

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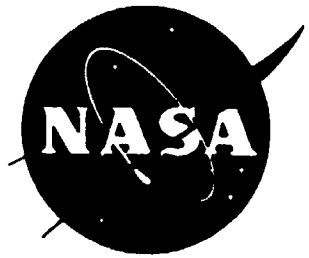
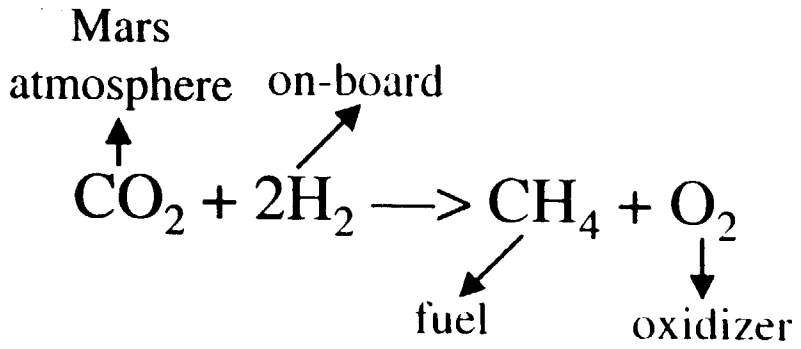
Application
In-Situ Propellant Production



- Use atmosphere from Mars to make fuel for return flight.
- Livingstone controller developed at NASA KSC.
- Components are tanks, reactors, valves, sensors...
- Exposed several (known and unknown) modelling errors.
- Latest model is 10^{55} states.
- Live experience of V&V methods used by non-specialists.



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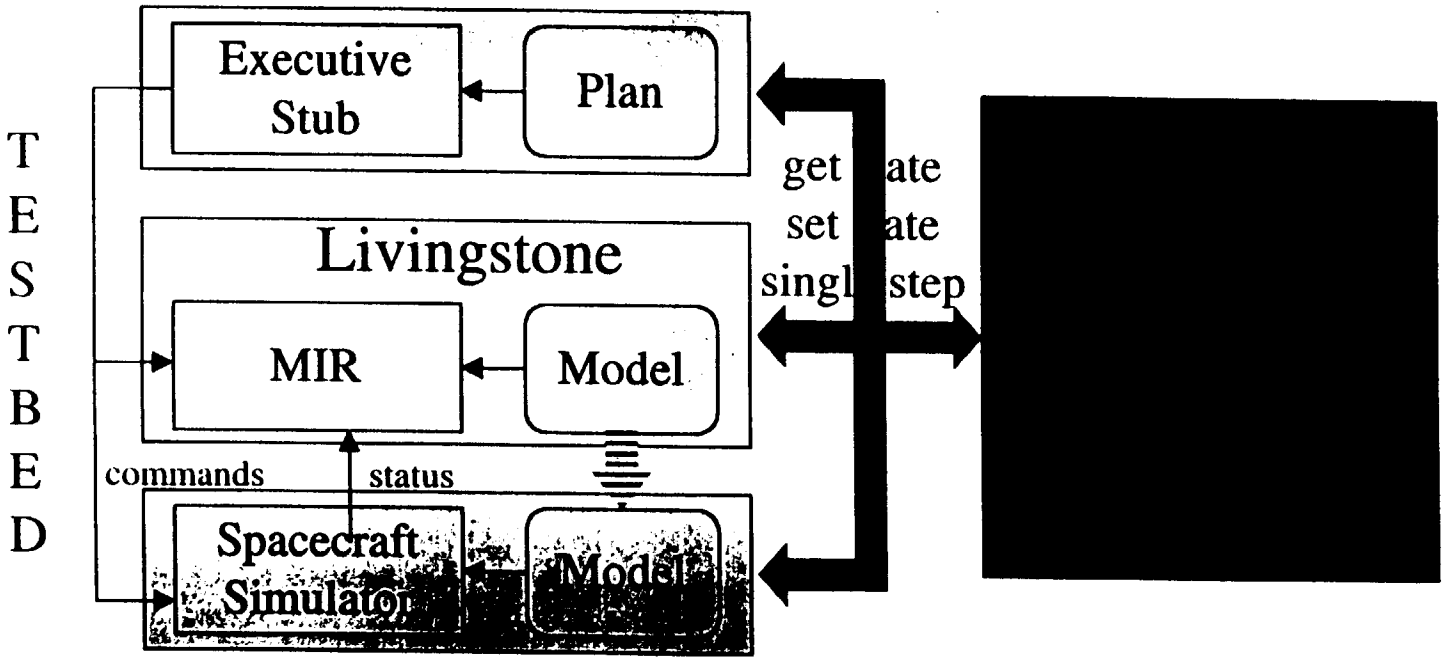
Closed-Loop Verification Principle



- Start from conventional testing (the real program).
- Instrument the code to be able to do full model checking (or as close as possible).

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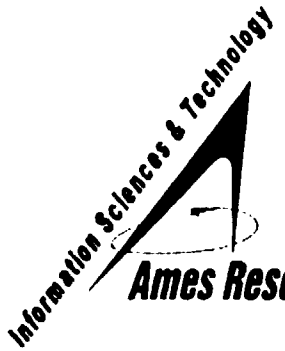
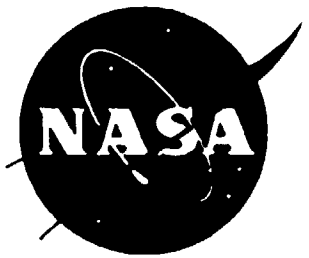


Livingstone PathFinder (LPF)



- Closed-loop verification for Livingstone.
- In Java, using Livingstone 2 (C++ via Java JNI).
  - Uses Livingstone 2 checkpointing.
- Scenario:

  (sequence of commands) × (choice of faults)
- Livingstone-based simulator.
  - Supports under-constrained models.
- Open API between testbed and model checker
  - Re-use parts of Java model checker.

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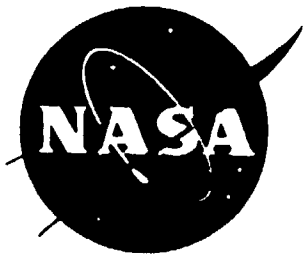
Publications and Presentations



- 3 Papers on Livingstone-to-SMV translator
  - Simmons & Pecheur, AAAI Spring Symposium (03/00)
  - Pecheur & Simmons, Goddard FAABS Workshop (04/00, book chapter in preparation)
  - Simmons & Pecheur, IROS Conference (11/00)
- 3 Presentations on V&V of ISPP
  - Engrand & Pecheur, Goddard FAABS workshop (poster, 04/00)
  - Engrand, RIACS V&V of A&A workshop (invited, 12/00)
  - Engrand, AAAI Spring Symposium MVI (03/01)
- 1 Survey paper on V&V of MBAS (to be submitted)
  - Pecheur, NASA/TM-2000-209602
- 2 Papers on ISPP including V&V
  - Gross et al., IAC 1999 (09/99)
  - Clancy et al., Technology 2009 (11/99)
- 2 Workshops on V&V of MBAS
  - RIACS V&V of Autonomous and Adaptive Systems (Pecheur, Simmons, Visser, 12/00)
  - AAAI Model-based Validation of Intelligence (Khatib, Pecheur, 03/01)
- 2 Tutorials on V&V including V&V of MBAS
  - Pecheur, Simmons, Visser & Havelund, Langley FM 2000 (06/00)
  - Pecheur & Visser, ASE 2000 (09/00)

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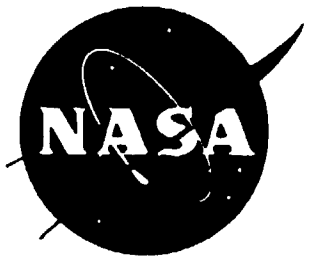
Future Directions



- MPL2SMV:
  - FMEA analysis from Livingstone models.
  - Use SAT-solving and bounded model checking.
  - More user guidance (patterns, verification process tool).
- Temporal Queries:
  - Can it be made useful? More experiments, improve tool.
- Livingstone PathFinder:
  - Explore different exploration strategies, case studies.
- Publications
  - survey paper, temporal queries, closed-loop verification, ...

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