Massachusetts Institute of Technology

Model-based Monitoring and Diagnosis of Systems with Software-Extended Behavior

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Model-based Embedded & Robotic Systems

Diagnosing Complex Systems

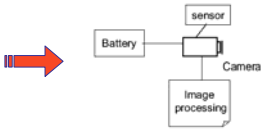
MERS Rover Testbed

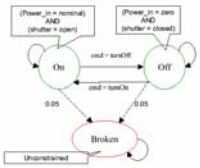
Mars Polar Lander

Earth Observing One

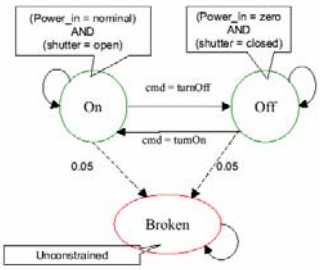
Vision-based Navigation Scenario

MERS Rover Testbed





Vision-based Navigation Scenario



Vision-based Navigation Scenario

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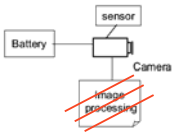
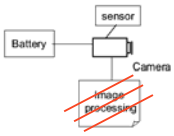


Failure Probability	
10%	Battery
5%	Camera
1%	Sensor

Vision-based Navigation Scenario

MERS Rover Testbed



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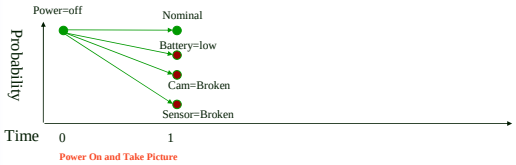

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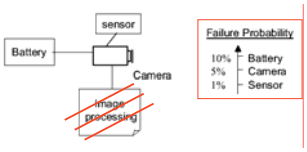

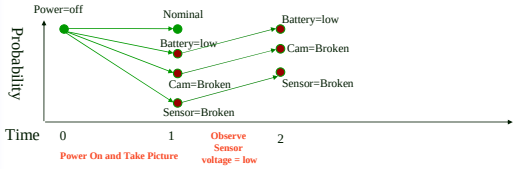

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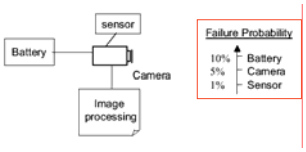

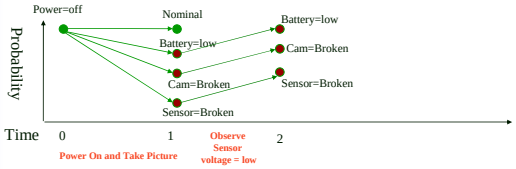

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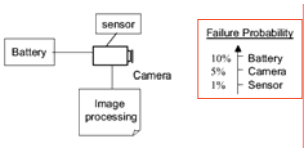
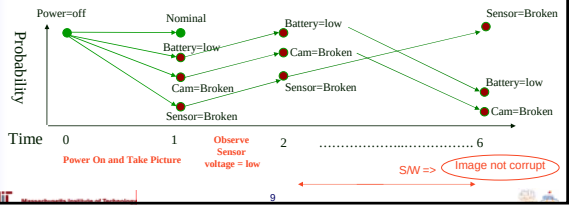




Problem and Challenges

Problem:

Given observations, commands, and behavior models:

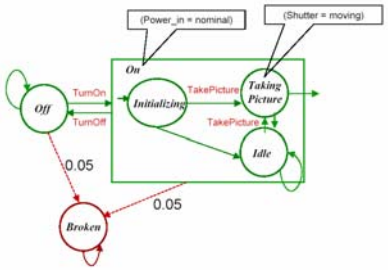
Track the most likely *state trajectories* of the software-extended system over time

Challenges:

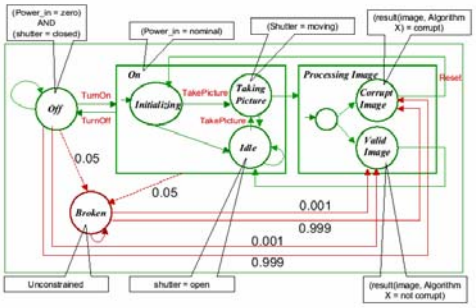
1. Monitor complex behavior
2. Delayed symptoms
3. Efficiency

Modeling Framework

Probabilistic, Hierarchical Constraint Automata (PHCA)
[Williams, Chung, Gupta 2001]

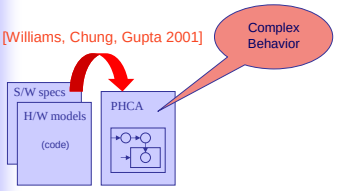


Modeling Framework



Diagnosis Process

[Williams, Chung, Gupta 2001]



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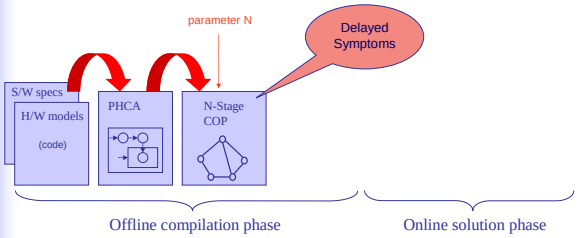
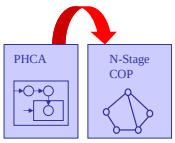
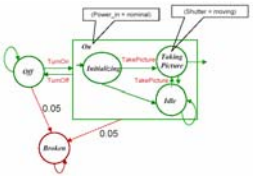


Encoding PHCA as COP





Valued Constraint Optimization Problem (COP):

- **Variables**
  - Location variables, PHCA variables, Auxiliary variables
- **Domains**
  - Example: *{Marked, Unmarked}* for location variables
- **Valued constraints*** *[Schiex, Fargier, Verfaillie,1995]
  - Encode PHCA + Execution semantics
- **Solve for Location Variables, maximizing value of State Trajectory**

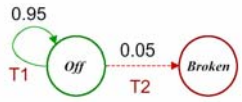
Valued COP

A *constraint optimization problem* (COP) consists of a set of variables $X = \{X_1, ..., X_n\}$ with a corresponding set of finite domains $D = \{D_1, ..., D_n\}$, a set of constraints $R = \{R_1, ..., R_m\}$, a valuation structure $(E, \leq, \oplus, \bot, \top)$, and functions $F = \{F_1, ..., F_m\}$ mapping tuples of the constraints R to E. Each constraint $R_i \subseteq D_{i1} \times ... \times D_{ik}$ is defined over variables $\{X_{i1}, ..., X_{ik}\} \subseteq X$. The set E is totally ordered by $\leq$ with a minimum element $\bot \in E$ and a maximum element $\top \in E$, and $\oplus$ is an associative, commutative, and monotonic operation, with identity element $\bot$ and absorbing element $\top$. Each $F_i \in F$ is a function $F_i : R_i \to E$, mapping tuples of R_i to values in E. Functions F are thus called valuations of constraints R.

Probabilistic Valuation: $(E, \leq, \oplus, \bot, \top) = ([0,1], \max, \cdot, 1, 0)$

Value of solution: $V(t) = (\bigoplus_{i=1}^{m} F_i) \downarrow_Y)(t)$

PHCA Encoding Example

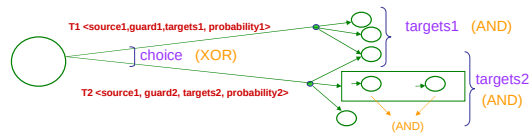


$$Off^t = Marked \Leftrightarrow ((\exists T \in \{T1, T2\} : T^t = Enabled) \wedge (\forall T' \in (\{T1, T2\} - \{T\}) : T'^t = Disabled)) \bigwedge$$
$$Off^t = Unmarked \Leftrightarrow (\forall T \in \{T1, T2\} : T^t = Disabled)$$

$$F_T(M) = \begin{cases} Prob(T_i) & if\ (\exists T_i^t : T_i^t = Enabled) \\ 1.0 & otherwise \end{cases}$$

Off^t	$T1^t$	$T2^t$	Probability
Marked	Enabled	Disabled	0.95
Marked	Disabled	Enabled	0.05
Unmarked	Disabled	Disabled	1.0

PHCA Encoding Constraints



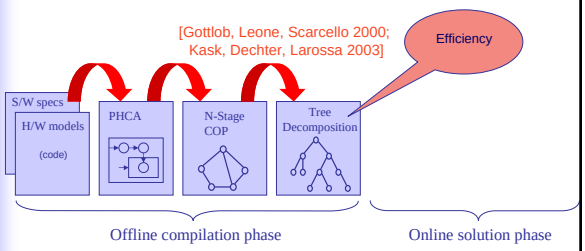
Categories of Constraints:

1. State consistency and transition guard consistency
2. Initial (t=0) constraints
3. Transition constraints
4. Marking constraints

⇒ We derive a total of 14 constraints (rules)

⇒ Instantiated for any PHCA, for any N-Stage time horizon

Diagnosis Process



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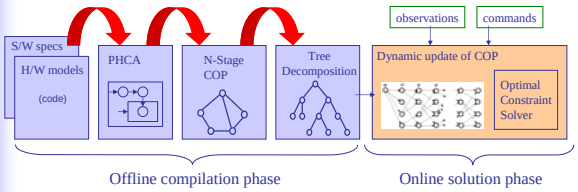
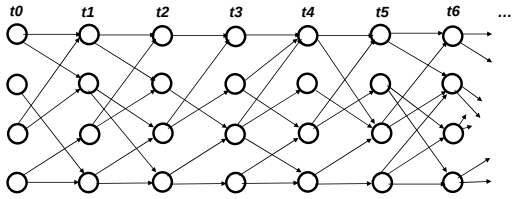


Online Diagnosis Phase

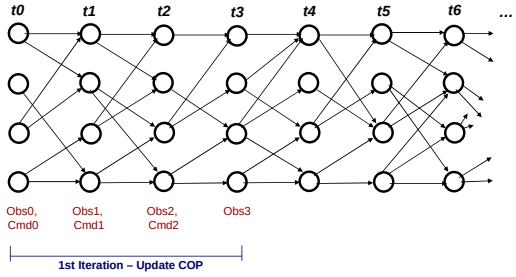
- Trellis diagram showing PHCA State Evolutions



- Online Loop
  - Update the COP
  - Solve the COP
  - Repeat

Online Diagnosis Phase

- N-Stage K-Best Trajectory Enumeration
  N=3 time steps; K=2 trajectories



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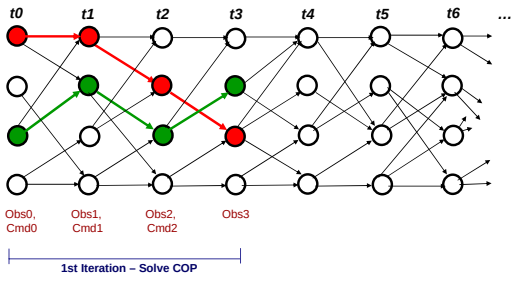

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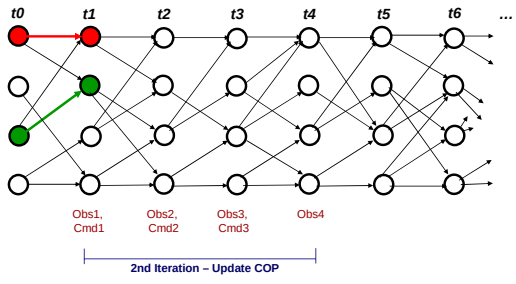

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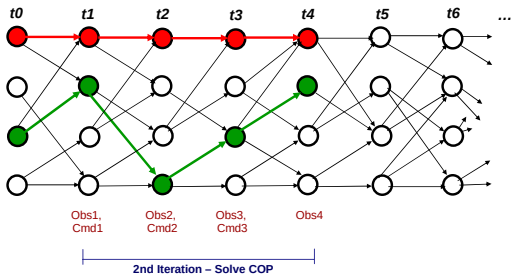

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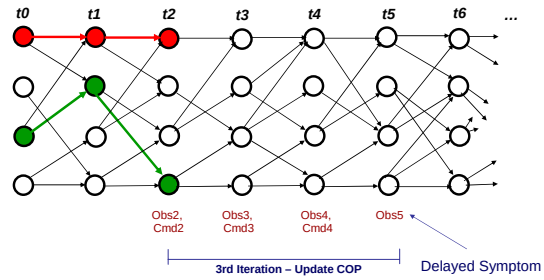

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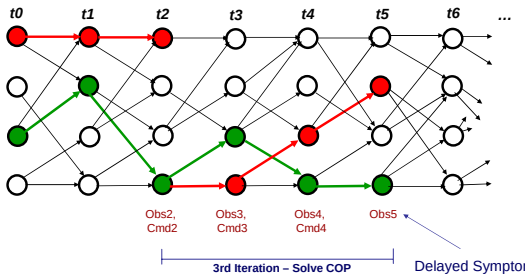

Demonstration Scenarios

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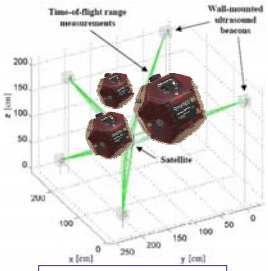
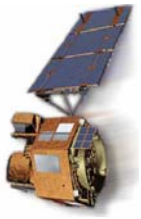
MIT SPHERES Testbed Models



-Global Metrology Subsystem
SPHERES 1 (5 components)
SPHERES 2 (18 components)

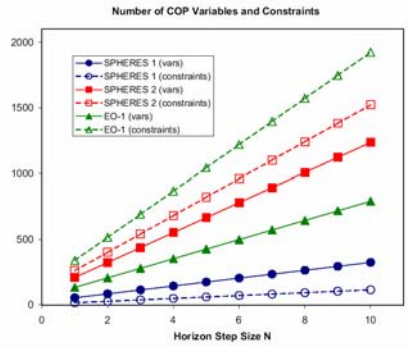
NASA Earth Observing One (EO-1) Models



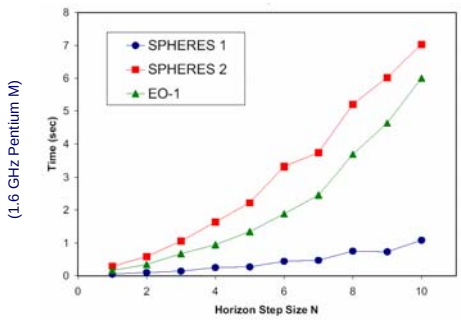
- Advanced Land Imager
- Hyperion Instrument
- Wideband Advanced Recorder Processor

EO-1 (12 components)

Results: Offline



Results: Online



Solver: [Sachenbacher and Williams, 2004]

Summary and Related Work

PHCA: [Williams, Chung, Gupta]
Delayed Symptoms: Livingstone2 [Kurien and Nayak]
Structure: [Darwiche and Provan; Dechter et al.]