Automatic Recovery from Failures and Attacks using Partially Observable Markov Decision Processes

William H. Sanders
University of Illinois

(joint work with Kaustubh R. Joshi, Matti A. Hiltunen, Richard D. Schlichting)
Outline

- **Motivation**
- **Driving Application**
  - A problem looking for a (better) solution
  - Other infrastructures with similar problems
- **Model-based solution**
  - Probabilistic diagnosis
  - POMDP-based recovery
  - Stability and performance properties
  - Results
- **Future work**
- **Conclusions**
Motivation

• System management must be automated:
  - Driving factors speed of response, cost, and amount of data
  - Needed for true intrusion tolerance

• Drivers of change
  - Failures and attacks
  - Changing workloads and requirements
  - Changing resources

• Dealing with change
  - Recovery - rapid response crucial
  - Rejuvenation - preventive maintenance and reconfiguration
  - Only different in the types of indicators used
Motivation, cont.

What does the monitor output mean? Confidence level?

What are the possible effects of this action (positive/negative)? What’s its cost?

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Automatic Intrusion Tolerance

- Triggers, actions, and metrics
- Fundamental cost/benefit tradeoff
  - When is change needed, what benefits does it bring?
  - Simplest example - does adaptation take system to a “good” state?
  - Need a way to encode some operator knowledge (e.g., which actions may correct a problem)
  - Need metrics (cost/rewards) to perform this automatically
Problem: Monitoring and operator alerting for a complex internet-based system

Home grown + COTS components:
- Firewalls, load balancers, web servers, JMS servers, databases, Voice Genie, SMTP/IMAP servers,..
- Network elements: routers, switches, links
- External services

Different independent monitors for some individual components and for end to end service functionality

Problems:
- Lots of operator alarms (one problem, multiple alarms)
- False positives
- Poor localization (i.e., what is the real problem)
- Not great fault coverage

Goal: Make things better
Driving Application: AT&T’s Enterprise Messaging Network (EMN)

Component Monitor

Internal Mail Path Monitor

JMS

EMN Server

Database

any host

HostMon

ITI

VG Monitor

Voice Genie

Voice Genie

Firewall

Firewall

Load balancer

Load balancer

SMTP IMAP

SMTP IMAP

SMTP IMAP

SMTP IMAP

Fax Gateway

Fax Gateway

Pager Gateway

Pager Gateway

SMS Gateway

SMS Gateway

HTTP Gateway

HTTP Gateway

JMS

JMS

Driving Application: AT&T’s Enterprise Messaging Network (EMN)
Previous Solution

- Collect the outputs of all the monitors into a centralized syslog
  - Disable direct operator alerting from the individual monitors

- A MasterMonitor program continuously reads the log, forms an estimate of the system state, and alerts operators when necessary
  - Various heuristics used to combine information
  - Use passage of time to deal with false positives
  - Combine outputs from multiple monitors to eliminate possibilities (i.e., narrow down the faulty component)
Lessons Learned

- Diagnosis can be difficult: Which component is faulty?

Maybe: A or D

However, could be any, because M1 and M2/M3 may not detect the same fault types

Complexity of coding such rules was getting out of hand
Challenges with Monitors & Diagnosis

- **Monitors**
  - Different system monitors detect different types of problems => fault hypotheses
    - Monitor outputs and recovery actions can be characterized in terms of these fault hypothesis
  - Monitors do not always detect the problem
    - Must have notion of fault coverage (probability)
  - A general methodology for monitor output fusion is needed

- **Diagnosis**
  - Typically no absolute knowledge of faulty component
    - Recovery actions must be used to improve diagnosis
    - Performing more monitoring is often a good action to take
  - Automated system must know when to give up
Challenges in Recovery

- Opaqueness makes diagnosis difficult
  - Multiple tiers span administrative domains
  - Poor localization, false positives and negatives, imperfect coverage
  - Each monitoring technique has different strengths
  - Result: uncertainty about true system state

- Multiple choices of recovery actions
  - Varying cost
    - Restart component vs. reboot host
    - Act now or wait until later?
    - Ordering constraints between component restarts
  - Varying benefit - not all failures are equal
    - Different components are valued differently depending on their customer impact.

- What if the automated system becomes unstable?
  - Ad-hoc vs. theoretically founded approaches
Abstracted Example: An E-commerce System

- Fault models: fail-silent (crash), non fail-silent (zombie) faults
- Recovery Actions: restart component, reboot host.
- Individual component monitors: only detect crashes
- End-to-end path monitors: detect crashes and zombies but poor localization
- Recovery Cost: fraction of “lost” requests (i.e. user-perceived availability)
Recovery Engine Architecture

Online Computation

- Bayesian Update
- New Belief State ($p$)
- Action Chosen
- Trajectory Tree Computation
- POMDP Bounds

Offline Computation

- Model of Faults, Actions, Monitors, Rewards
- Compute RA-Bound
- RA-Bound
- Bounds Improvement (sim model)

Engine Operation

- Wait for monitor alert
- Diagnose
- Choose Action
- Execute Action
- Done?
- Execute monitors
- Recovery Engine

- Action that maximizes value function tree is chosen at each step
- What to use for remaining cost at the leaves of the tree?
  - Zero cost, heuristic cost, bound?
Probabilistic Bayesian Diagnosis

- Precise diagnosis often impossible due to monitor limitations
- Use Bayes rule to compute “diagnosis vector” \{P[fh_1], \ldots , P[fh_n]\}
  - Each entry: probability of \(fh\) given current monitor outputs
  - Using monitor coverage models \(P[m|fh]\) and prior diagnosis
  - If no prior knowledge of which fault, use \(P[fh]=1/|FH|\)
  - Keep track of commonly occurring faults to choose better priors
Monitor Models

- Need to know coverage: $P[m|fh]$
- Dependency graph based
  - Probability of touching failed node in a request graph
- Queuing network based
  - Probability of observed response time, load
  - Statistical test
- Statistically learned models in general
A POMDP is a tuple \((S,A,O,p(s'|s,a),q(o|s,a),c(s,a))\)

- **States** \((S)\): which fault (or null fault) has occurred
- **Observations** \((O)\): monitor outputs \(\{o_m\}\)
- **Transition function** \(p(s'|s,a)\): effect of recovery action on system and fault state
- **Observation probabilities** \(q(o|s,a)\): probability that \(o\) is generated (monitor models)
- **Cost Function** \(c(s,a)\): recovery cost, e.g., availability, requests lost/denied etc

**System evolution**

- \((s_0,a_0,o_0,...s_n,a_n,o_n)\)
- But controller can’t see \(s\) - it tracks “belief state”
- Belief state \(\pi = [\pi(s_0),...\pi(s_n)]\): state occupancy probability vector (i.e., diagnosis vector)
Optimal Value Functions

- **Policy** $\rho$ specifies what action to take in each belief state
  - Optimal policy $\rho^*$ minimizes mean accumulated cost starting from all belief states
  - $\rho^*$ is Markovian in belief state (i.e. current diagnosis vector)
- **Optimal $\rho^*$ computation**
  - Bellman dynamic programming recursion
  - $C_m(\pi) = \min_a \{c(s,a) + \mathbb{H}_s[C_m(\pi')]\}$
  - $p'(\pi',\pi,a) = \sum_sq(o|s,a)\sum_s\pi(s')p(s|s',a)\pi(s')$ if $\pi' = \text{BayesNextBelief}(\pi,a,o)$
    - $= 0$ otherwise
  - $c'(\pi,a) = \sum_sc(s,a)\pi(s)$
- **Tractability is a problem.**
  - Dynamic programming defined over all $\pi$
  - There could be infinite $\pi$ even for trivial $S$!
  - Exact techniques scale only up to few thousand states
Finite Depth Online POMDP Solution

Leaves are assigned heuristically chosen or bounded cost
Recovery Engine Guarantees

- Desired Guarantees:
  - **Safety**: recovery engine does not execute unsafe actions
  - **Guaranteed recovery**: engine does not terminate before recovery is successful (can only be guaranteed w.r.t. model)
  - **Finite termination**: recovery terminates in a finite amount of time
  - **Optimal performance** (ideal): recovery cost is minimized
  - **Performance guarantee** (practical): recovery cost may not be optimal, but is lower than a promised value

- POMDP based recovery engine using finite depth solution
  - Safety can be ensured at model level by disabling dangerous actions
  - Heuristic value at leaves: we can make no guarantees
  - Lower bounds of true value: probabilistically guaranteed recovery, finite termination, average performance guarantee
Value Function Lower Bounds: RA-Bound

- Previously: Bounds on discounted rewards
  - Discounted reward: \( V(\pi) = \max_a \{ r(s,a) + \beta \mathbb{H}_s[V(\pi')] \} \)
  - Previous techniques: BI-POMDP, blind action
  - Always finite - even when controller never terminates!
  - Difficult to determine “good” \( \beta \) - weak relation to reality

- New (DSN’06): Bounds on undiscounted accumulated reward
  - Value function may be infinite
  - BI-POMDP, blind action not always finite even for finite valued recovery models
  - We develop a new bound (RA-bound) and conditions under which it works for recovery models
  - Can evaluate risk of terminating recovery too early
Key Practical Benefits

- **Model based** - allows separation of concerns monitoring and recovery during specification
- **Reward based recovery considers both cause and impact** - precise root cause identification may not be critical
- **Recovery is Sequential** - natural way to deal with mistakes
- **Ability to look multiple time-steps ahead** - knows when to wait for additional information
- **Formal framework** - provides strong guarantees about stability and goodness of adaptation
Greedy vs. POMDP (heuristic): Per-Fault Metrics (SRDS ’05)

**Recovery Time**
- **Residual Time**
- **"Extra" Recovery**

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>SSL1</th>
<th>SSL2</th>
<th>MSL1</th>
<th>MSL2</th>
<th>MSL3</th>
<th>Oracle</th>
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**Cost: % Increase of lost requests over oracle**

<table>
<thead>
<tr>
<th>Percent Cost Increase (%)</th>
<th>SSL1</th>
<th>SSL2</th>
<th>MSL1</th>
<th>MSL2</th>
<th>MSL3</th>
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<td>SSL2</td>
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<tr>
<td>MSL3</td>
<td>120</td>
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**Algorithm Running Time (msec)**

<table>
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<th>SSL1</th>
<th>SSL2</th>
<th>MSL1</th>
<th>MSL2</th>
<th>MSL3</th>
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**Extra Monitor and Actions Calls**

- **Recovery Actions**
- **Monitor Calls**

<table>
<thead>
<tr>
<th>Monitor Calls per Fault</th>
<th>SSL1</th>
<th>SSL2</th>
<th>MSL1</th>
<th>MSL2</th>
<th>MSL3</th>
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<tr>
<td>SSL2</td>
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<tr>
<td>MSL3</td>
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**Extra Monitor and Actions Calls**

- **Recovery Actions**
- **Monitor Calls**

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<th>MSL3</th>
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<td>MSL2</td>
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<td>MSL3</td>
<td>0.5</td>
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POMDP (heuristic vs. bounds, zombie only) (DSN’06)
POMDP (heuristic vs. bounds, zombie), cont. (DSN’06)
Model extensions:
- Continuous time: allowing independent system evolution

Engine extensions:
- Dealing with real monitors’ outputs: textual, non-standard
  - Combine rule-based and probabilistic reasoning
  - Rules good when no uncertainty of the problem
- Some monitors cannot be invoked at will
- Must wait for the “next scheduled” output
  - Sometimes monitors only give failure alarms but do not report recovery - Absence of alarm for a period of time = all OK
- System specification in general format (XML)
  - Components, their relationships, monitors, fault hypotheses, coverage, allowed actions, ..
  - Different system configurations
- Load-aware monitors for performance failures (queuing model based)
Conclusions

• A model-based solution for system diagnosis and automatic recovery develop based on needs identified in a real system (SRDS 05)
• New technique developed for solving models efficiently and accurately (DSN 06)
• Extensions underway to address issues in realistic systems
  - Key concern: building appropriate models
• Other application areas possible; evaluation part of future work
Questions?

Bill Sanders

whs@uiuc.edu
www.iti.uiuc.edu
www.perform.csl.uiuc.edu