Three-Valued Asynchronous Distributed Runtime Verification

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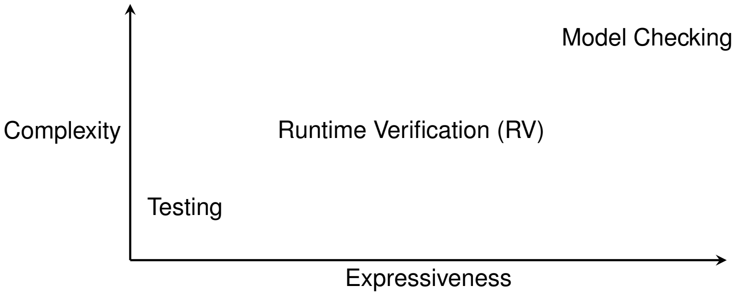
Introduction



Challenges of Distributed RV in Asynchronous Systems

There are various encountered when doing RV in asynchronous distributed systems, for example:

- different execution speed of agents
- inherent non-determinism in execution order
- information have to reach the monitor (communication overhead)
- one centralized or many decentralized monitors?

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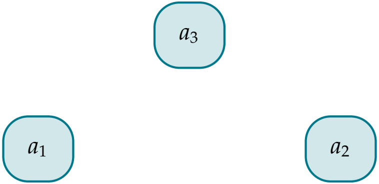
System Model



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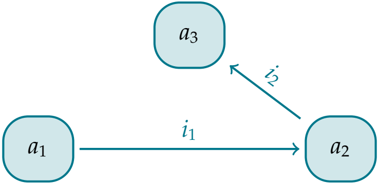

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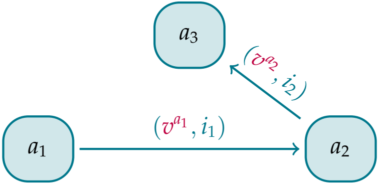
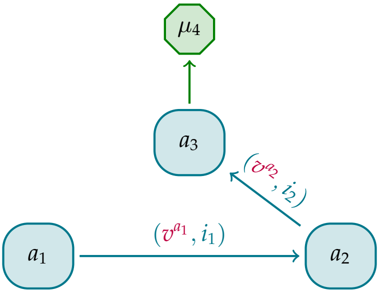
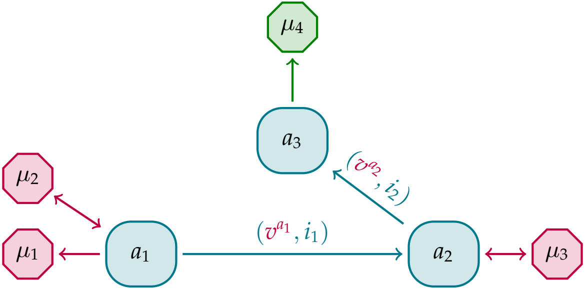


System Model



System Model



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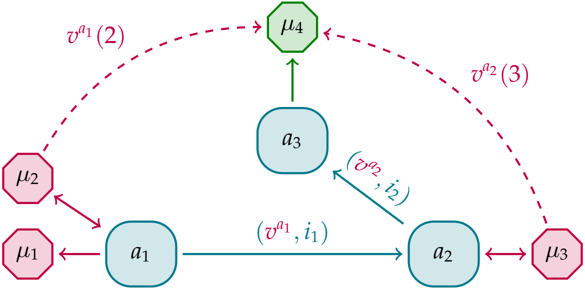

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Linear Temporal Logic (LTL) and Past Operators

$w = w_0 w_1 w_2 w_3 w_4 \cdots \in \Sigma^\omega$ execution trace (word)

Set of propositions and boolean operators negation ($\neg$) and or ($\vee$).

Future operators:

- Next ($\bigcirc$)
- Until ($\mathcal{U}$)

Past operators:

- Previous ($\ominus$)
- Since ($\mathcal{S}$)

Three-valued LTL over finite traces (LTL_3)

A. Bauer, M. Leucker, and C. Schallhart,

"Runtime Verification for LTL and TLTL"

$$[\![w \models \varphi]\!]_{\text{LTL}_3} = \begin{cases} \top & \text{if } \forall u \in \Sigma^\omega : wu \models_{\text{LTL}} \varphi \\ \bot & \text{if } \forall u \in \Sigma^\omega : wu \not\models_{\text{LTL}} \varphi \\ ? & \text{else} \end{cases}$$

The output of the LTL_3 semantics is only $\top$ or $\bot$ if every infinite extension of the trace is a model (not a model resp.) of the formula in LTL.

Past-Time Distributed Temporal Logic (ptDTL)

K. Sen, A. Vardhan, G. Agha, and G. Rosu,

"Efficient Decentralized Monitoring of Safety in Distributed Systems"

An Additional @-operator is used to spread properties over different agents.

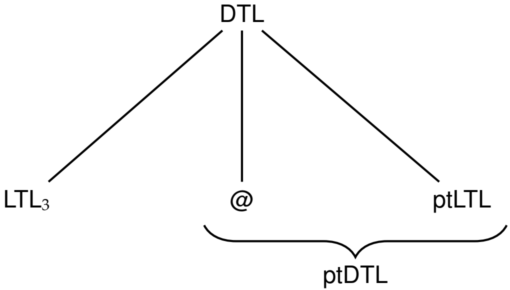
Example:

$$@_{a_1}(p\,\mathcal{S}\,@_{a_2}q)$$

$$\begin{array}{llllll} a_1: & \{p\} & \{p\} & \{p\} & \{\} & \{p\} \\ a_2: & \{\} & \{q\} & \{q\} & \{q\} & \{q\} \end{array}$$

Only safety properties monitorable with ptDTL

Distributed Temporal Logic (DTL)



DTL syntax

$$
\begin{array}{rccccccccc}
\chi ::= & @^{\mathrm{ft}}_{a_1}\varphi & \mid & @^{\mathrm{pt}}_{a_1}\psi & & & & & \\
\varphi ::= & \mathrm{true} & \mid & p & \mid & \neg\varphi & \mid & \varphi \vee \varphi & \mid \\
 & \bigcirc\varphi & \mid & \varphi\,\mathcal{U}\,\varphi & \mid & @^{\mathrm{ft}}_{a_2}\varphi & \mid & @^{\mathrm{pt}}_{a_2}\psi &
\end{array}
$$

DTL semantics

$@_a^{\mathrm{pt}}\varphi$ formulas are evaluated with ptDTL semantics.

$@_a^{\mathrm{ft}}\varphi$ formulas are evaluated similar to LTL_3 with DTL_ω replacing LTL.

DTL_ω works as follows:

- all operators besides $@_a^{\mathrm{ft}}$ and $@_a^{\mathrm{pt}}$ are evaluated as in LTL
- a subformula surrounded by $@_a^{\mathrm{pt}}$ is evaluated on agent a as in ptDTL
- a subformula surrounded by $@_a^{\mathrm{ft}}$ is evaluated on agent a as in DTL

Values from other agents are delivered using messages whose send and receiving points are marked in the runs of the agents.

DTL Advantages

The main advantages of DTL are:

- future and past operators

  $\Rightarrow$ higher succinctness

- three-valued semantics

  $\Rightarrow$ many more properties monitorable

- knowledge-vector and message symbols

  $\Rightarrow$ precise theoretical evaluation possible

Monitor Construction

Monitors for past formulas of DTL: algorithm from

K. Havelund and G. Rosu, “Synthesizing monitors for safety properties”

Monitors for future formulas of DTL: deterministic Moore machines (DMM) constructed as follows:

$$
\begin{tikzcd}
& \text{LTL} & \text{ABA} & \text{NBA} & \text{NFA} & \text{DFA} & \text{DMM} \\
& \varphi \arrow[r] & A_\varphi \arrow[r] & \overline{A}_\varphi \arrow[r] & \hat{A}_\varphi \arrow[r] & \tilde{A}_\varphi \arrow[dr] & \\
\varphi \arrow[ur] \arrow[dr] & & & & & & D_\varphi \\
& \neg\varphi \arrow[r] & A_{\neg\varphi} \arrow[r] & \overline{A}_{\neg\varphi} \arrow[r] & \hat{A}_{\neg\varphi} \arrow[r] & \tilde{A}_{\neg\varphi} \arrow[ur] &
\end{tikzcd}
$$

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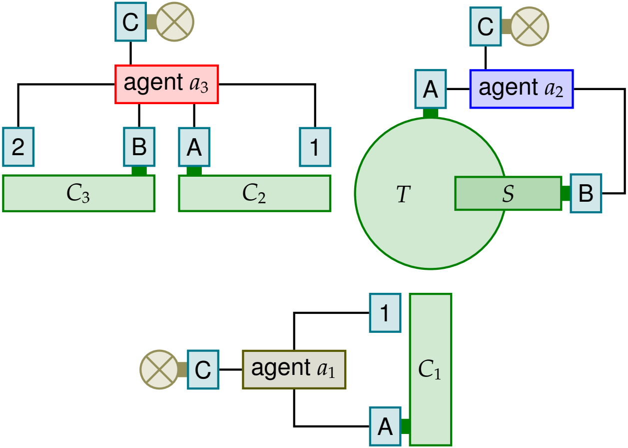
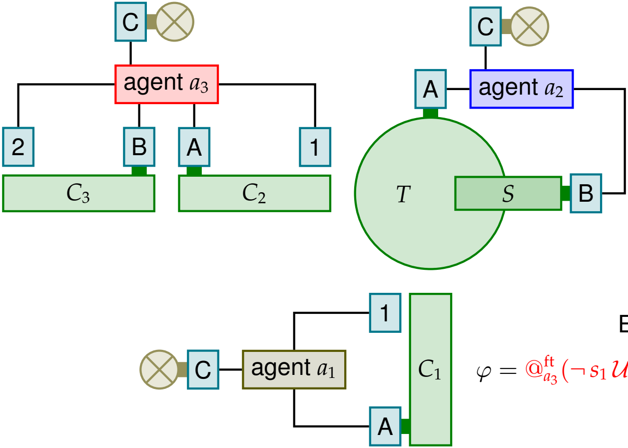
Case Study



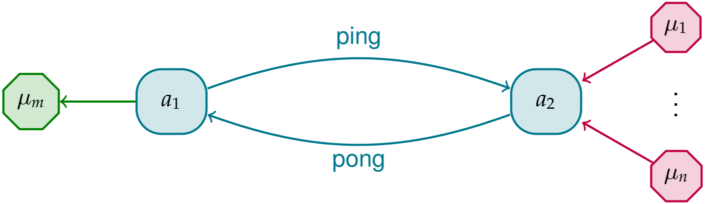
Case Study



Example:

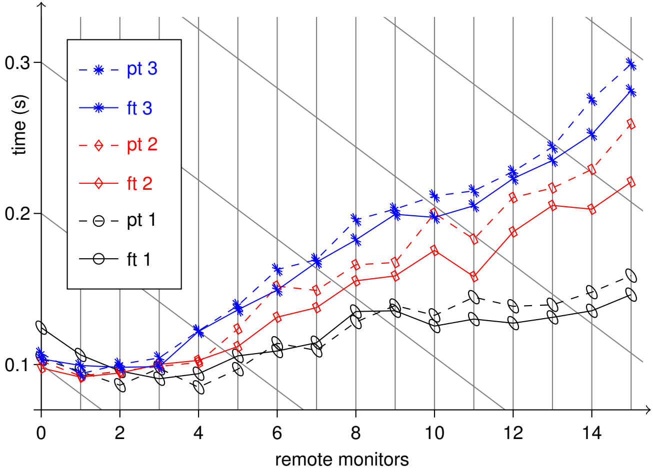
$$\varphi = @^{\text{ft}}_{a_3}(\neg s_1 \,\mathcal{U}\, @^{\text{pt}}_{a_2}(m_A \wedge \ominus @^{\text{pt}}_{a_1} \diamondminus s_1))$$

Benchmark



- Main monitor μ_m evaluates a formula of the form $@^{\text{ft}}_{a_1}(\varphi_1\,\mathcal{U}(\varphi_2\,\mathcal{U}(\ldots\mathcal{U}\,\varphi_n)))$ or $@^{\text{pt}}_{a_1}(\varphi_1\,\mathcal{S}(\varphi_2\,\mathcal{S}(\ldots\mathcal{S}\,\varphi_n)))$ for future or past case respectively.
- Every φ_i has the form $@^{\text{pt}}_{a_2}(p_{i_0}\,\mathcal{S}(p_{i_1}\,\mathcal{S}\,p_{i_2}))$ with the atomic propositions p_{i_0}, p_{i_1} and p_{i_2} and is evaluated by μ_i.

Benchmark


pt 3
ft 3
pt 2
ft 2
pt 1
ft 1
time (s)
0.3
0.2
0.1
0
2
4
6
8
10
12
14
remote monitors

Conclusion

We

- developed a system model which describes the distribution of monitoring data through messages,
- developed a new temporal logic DTL for distributed RV with a greater set of monitorable properties as ptDTL,
- programmed the transformation of DTL formulas into DMMs,
- used the created monitors for a case study to monitor a LEGO Mindstorms assembly line.