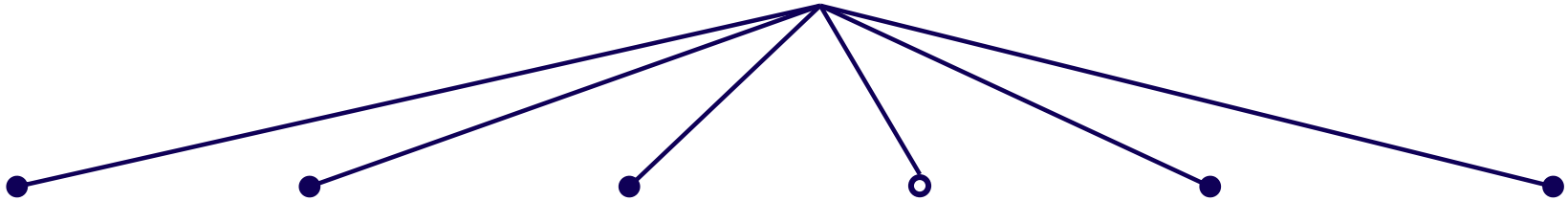
Modelling and Analysing SASs with SPL Techniques



Juliane Päßler, Maurice H. ter Beek, Ferruccio Damiani, Clemens Dubslaff, Einar Broch Johnsen, S. Lizeth Tapia Tarifa

U Oslo CNR-ISTI U Torino TU Eindhoven U Oslo U Oslo

JFT @ SPLC 2025, A Coruña, Spain

September 3rd 2025

Consiglio Nazionale delle Ricerche

Istituto di Scienza e Tecnologie dell'Informazione "A. Faedo"

FMT Formal Methods and Tools Lab

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REMARO
RELIABLE AI FOR MARINE ROBOTICS

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A Configurable Software Model of a Self-Adaptive Robotic System (Software Publication)
Juliane Päßler, Maurice H. ter Beek, Ferruccio Damiani, Einar Broch Johnsen, and S. Lizeth Tapia Tarifa
In: *Science of Computer Programming*, vol. 240, 2025. DOI: 10.1016/j.scico.2024.103221

What's in the two journal papers?

Analysing Self-Adaptive Systems as Software Product Lines

Model: SAS from underwater robotics domain as *probabilistic* FTS with *dynamic feature switching*
Analysis: reward and safety properties with the *feature-aware probabilistic model checker* ProFeat

Natural correspondence: SAS (*external self-adaptation* and *managed* + *managing* subsystem) and Dynamic SPL (*150% SPL family model* with a controller switching features during runtime)

https://pchrszon.github.io/profeat

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Feature-Oriented Modelling and Analysis of a Self-Adaptive Robotic System

Further modelling variants: operate at more altitudes and additional *vision* features: camera vs. sonar
Further analyses: using not only PRISM as backend, but also Storm for *parametric model checking* and *multi-objective queries* (achievability, numerical, Pareto) depending on analysed properties:

- Safety guarantees concerning mission duration and energy usage
- Impact of different environments on the safety guarantees
- Parameter synthesis to analyse the effect of environmental conditions
- Trade-offs between mission duration and energy usage
- …

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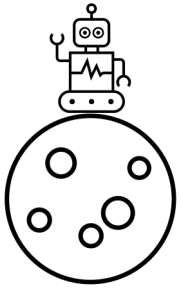
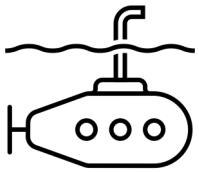
https://www.prismmodelchecker.org/

https://www.stormchecker.org/

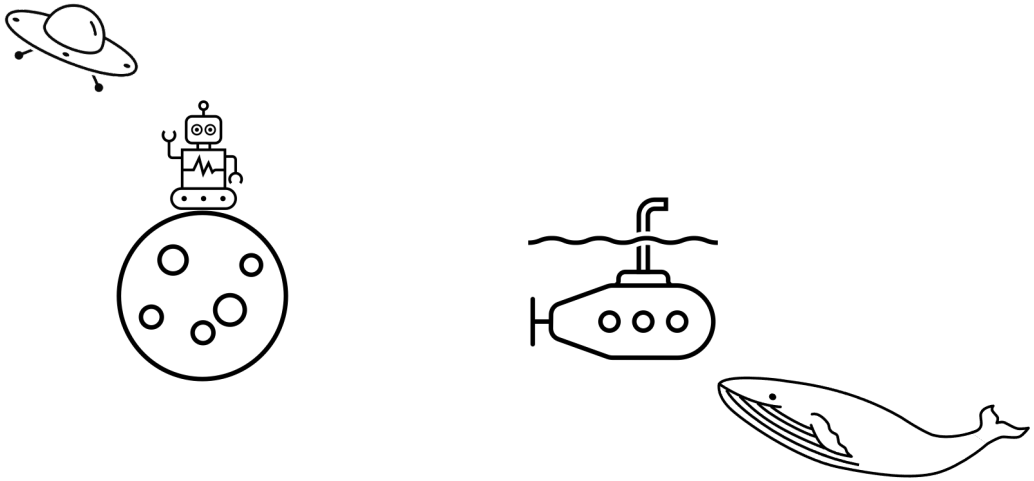
Self-Adaptive Systems





D. Weyns. An Introduction to Self-Adaptive Systems: A Contemporary Software Engineering Perspective. John Wiley & Sons, 2020.

Self-Adaptive Systems



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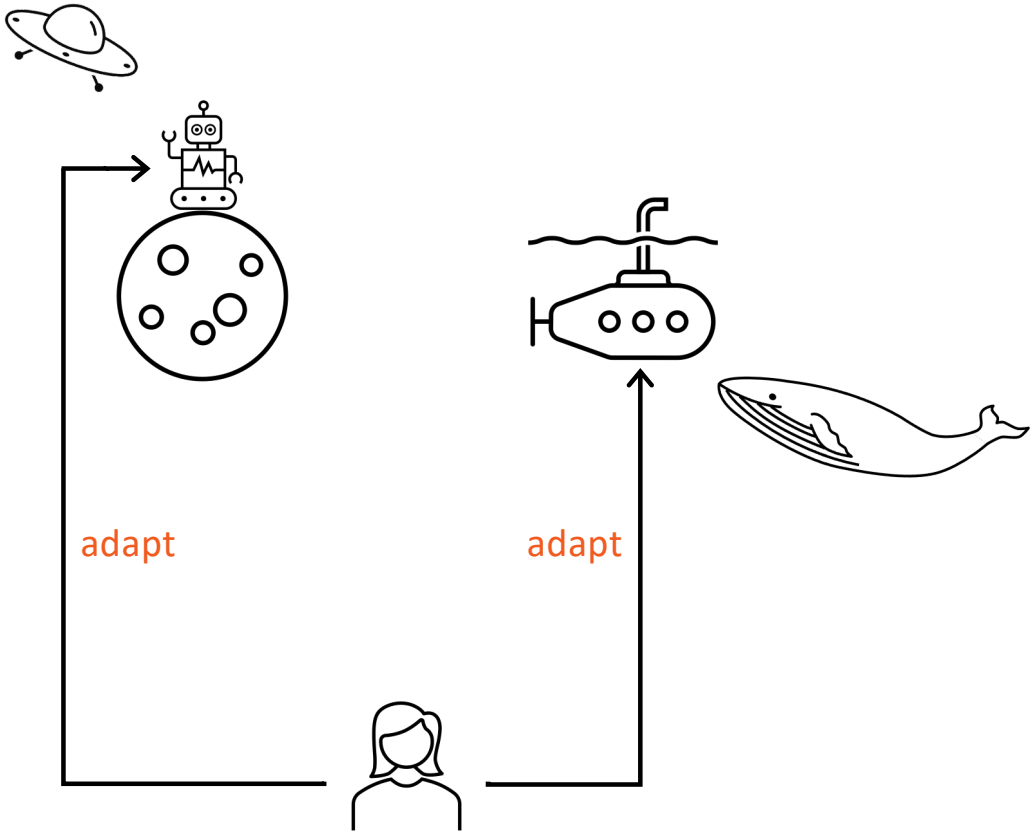

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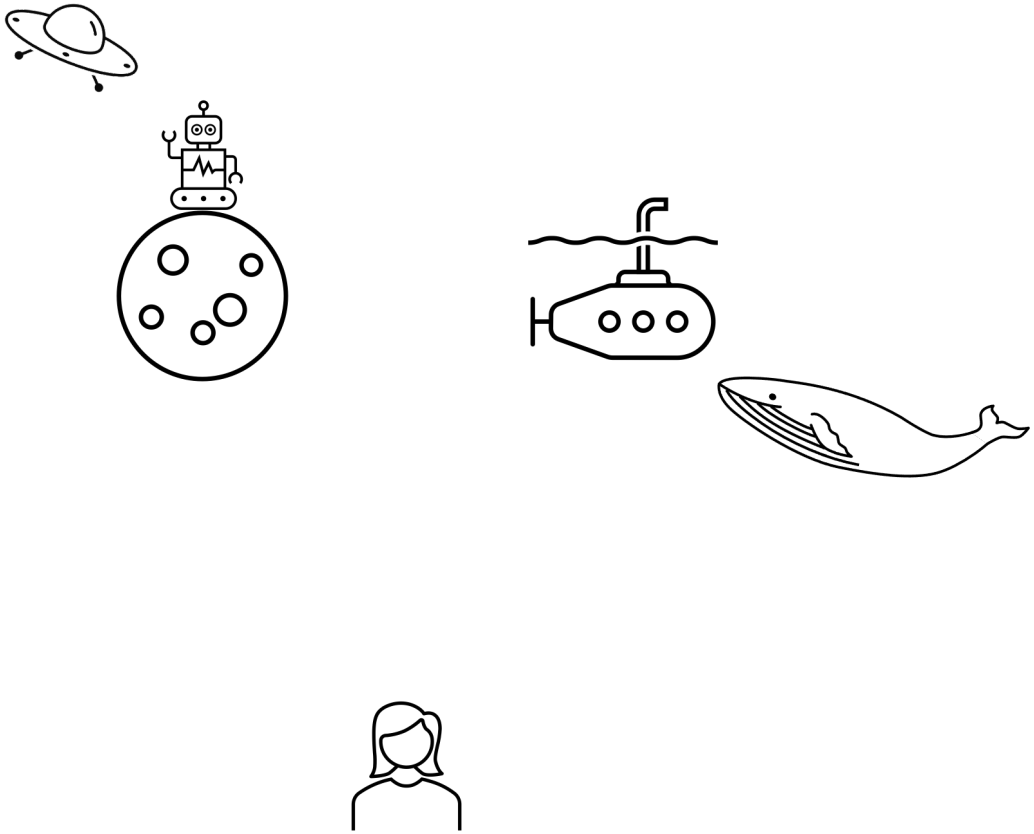

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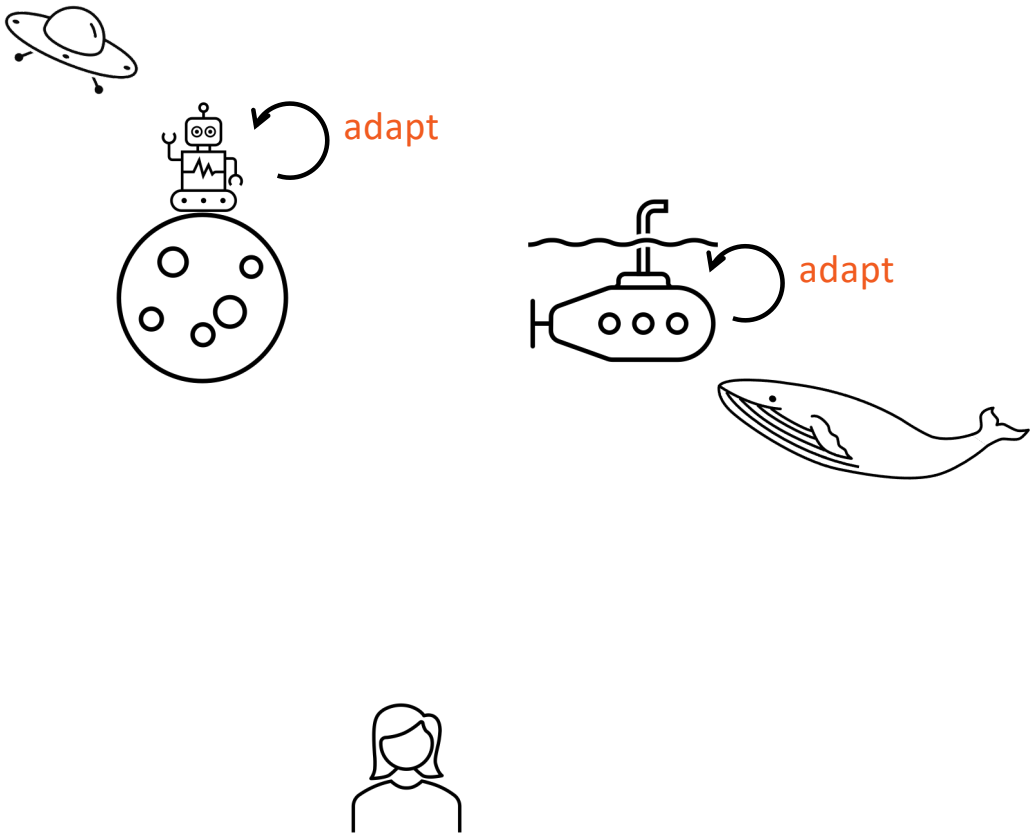

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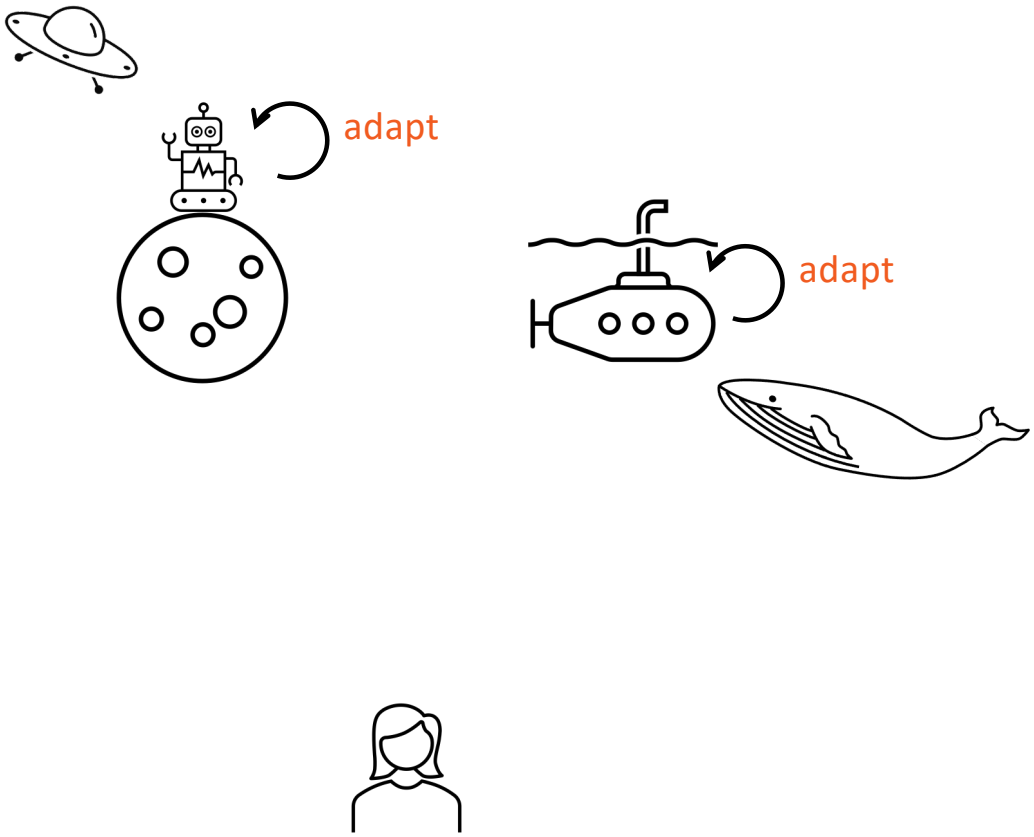

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- Perform mission autonomously
- Deal with unexpected situation

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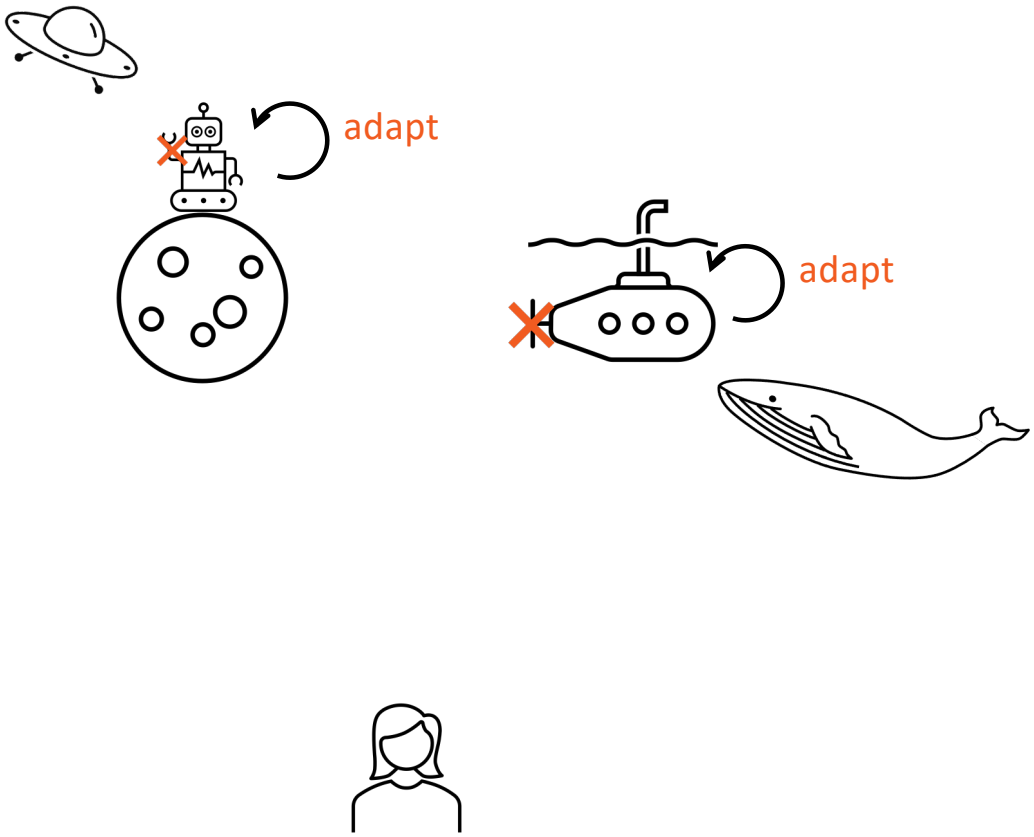

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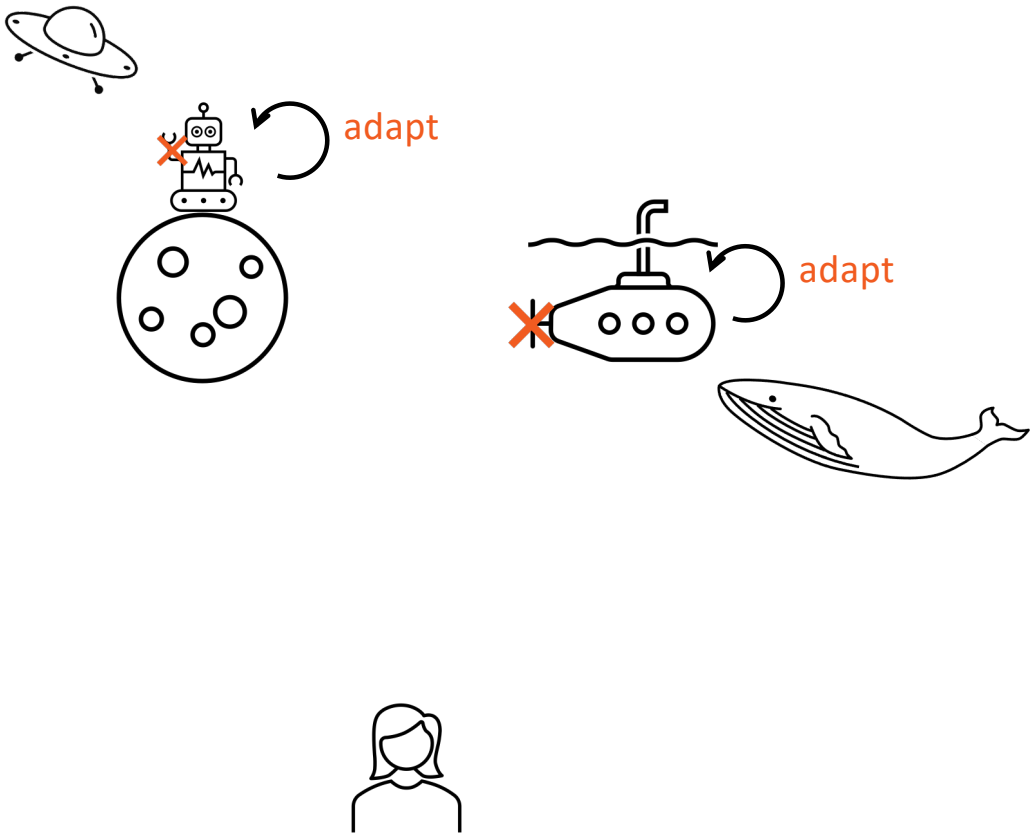

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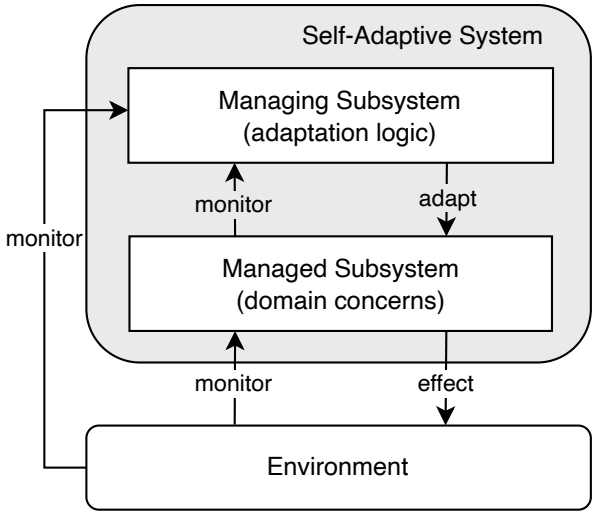

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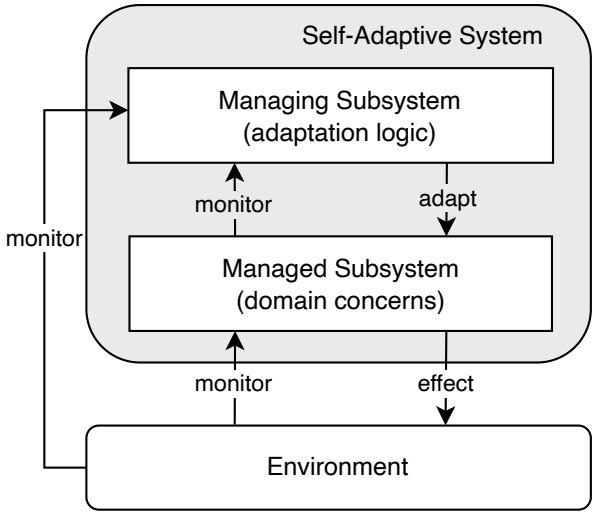

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Context

SASs:

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O. Aguayo, S. Sepúlveda, Variability management in dynamic software product lines for self-adaptive systems—A systematic mapping. Appl. Sci., 2022.

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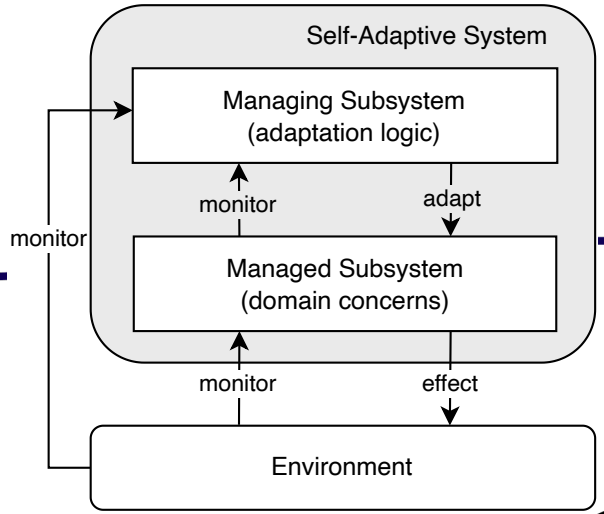
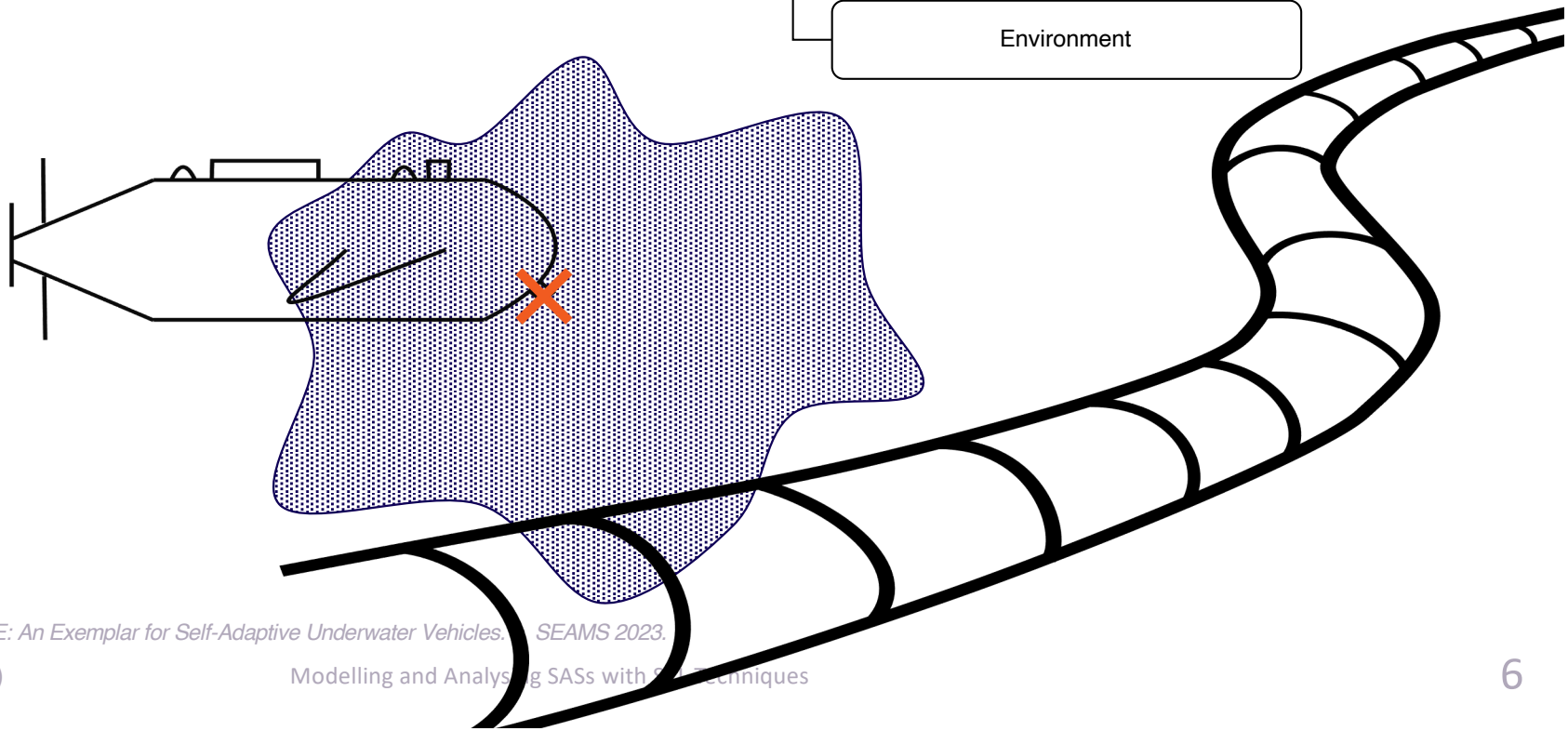
- K. Yoshimura, chief researcher at Hitachi, in his keynote address "*The 20-year journey of SPLE in Hitachi and the next*" during SPLC'23, presented the use of dynamic SPLs for autonomous robotic systems as a new industrial challenge

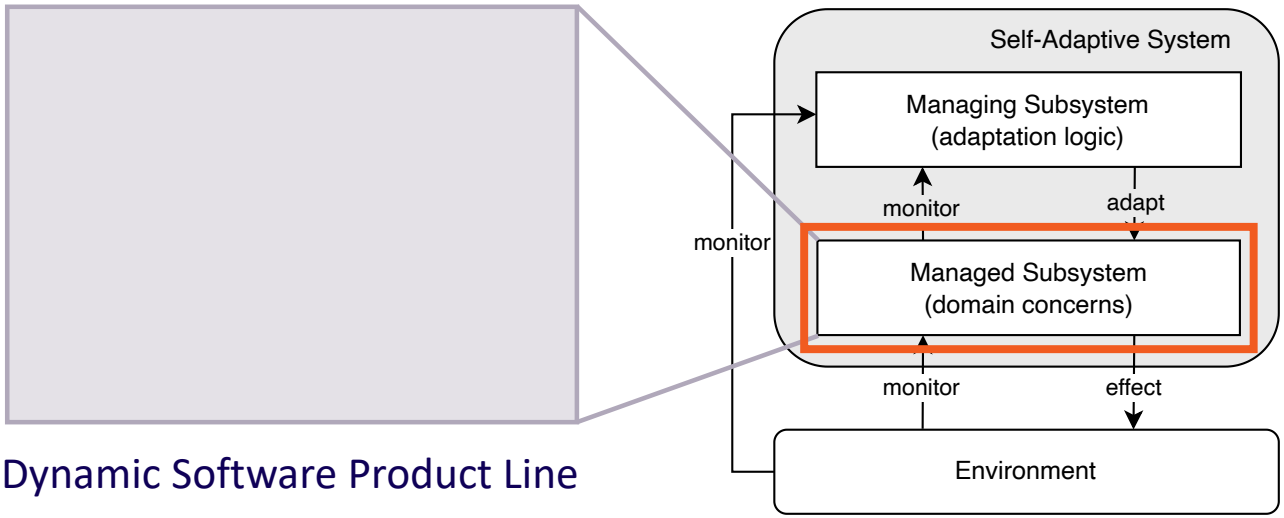
https://2023.splc.net/wp-content/uploads/2023/09/SPLC2023_Keynotes-1.pdf

Running Example from Literature



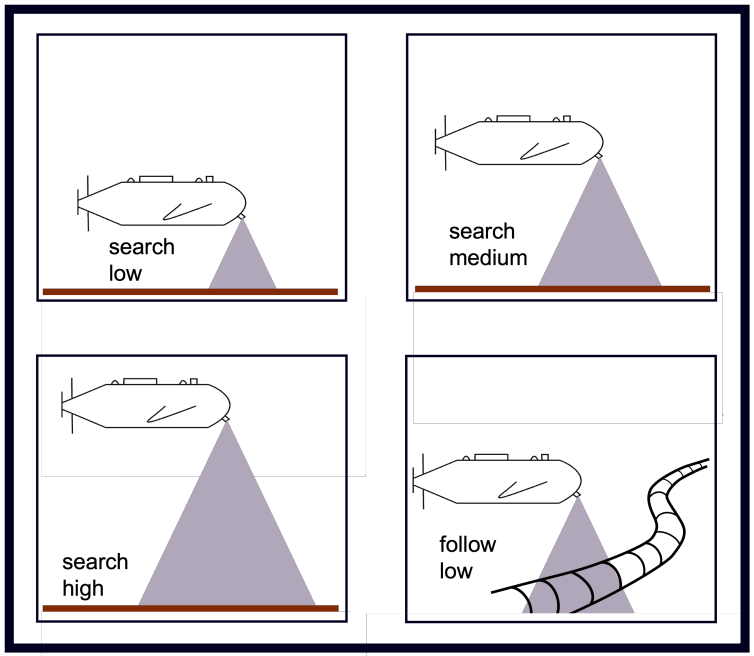


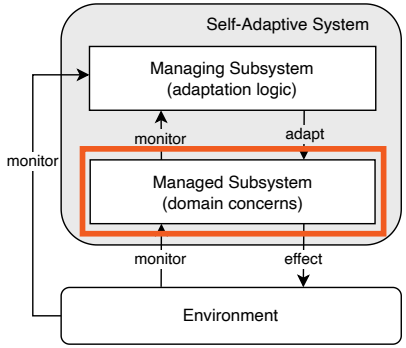
Modelling



Dynamic Software Product Line

Managed Subsystem: Variability





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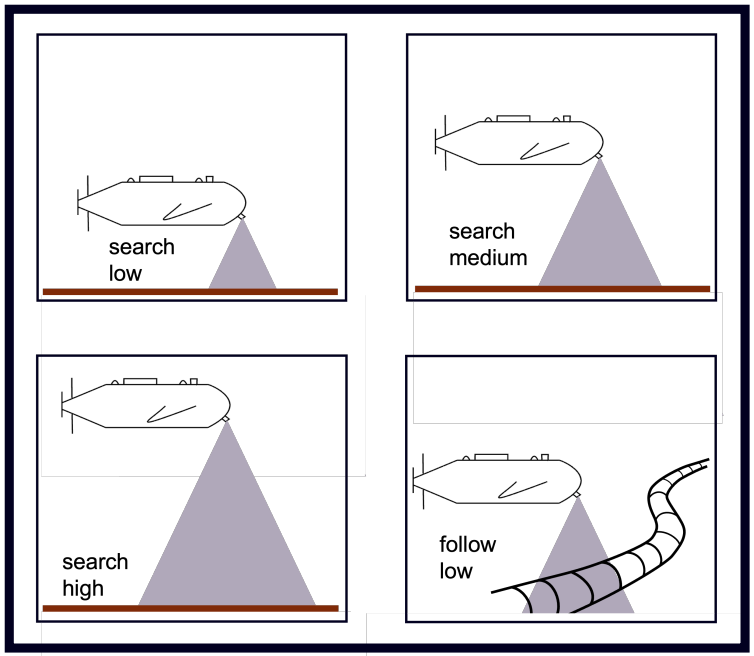
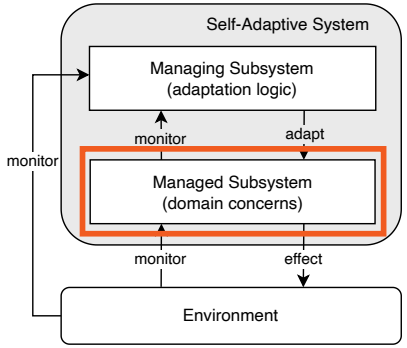


Configurations distinguished by features



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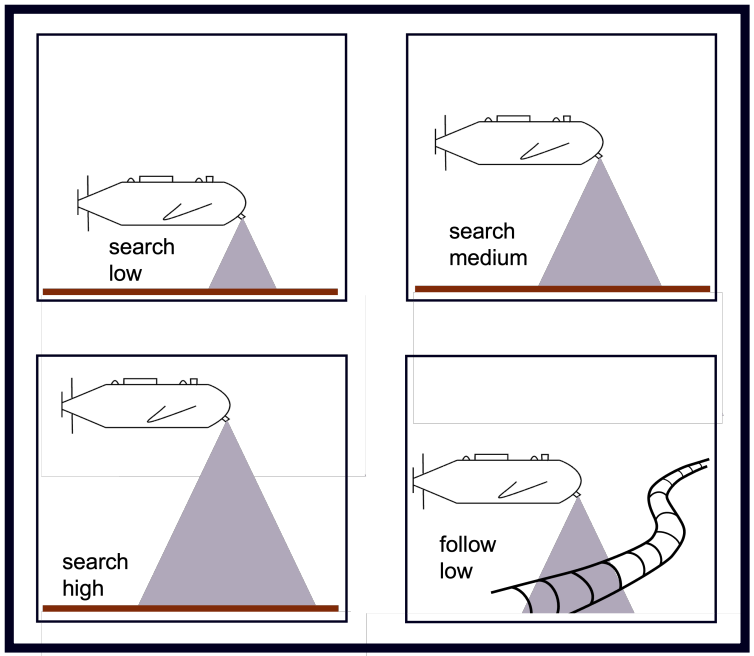

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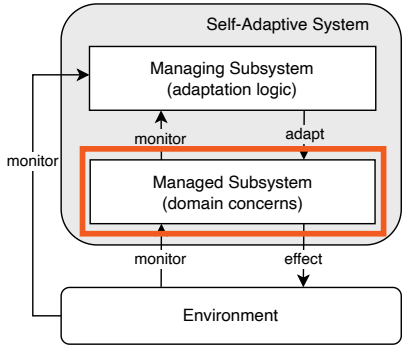
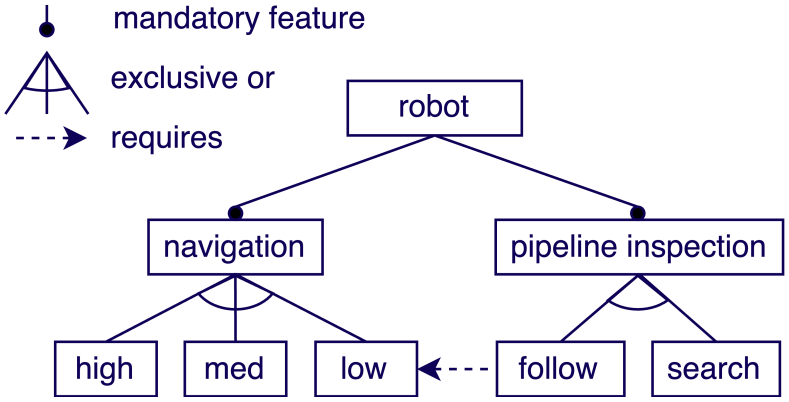
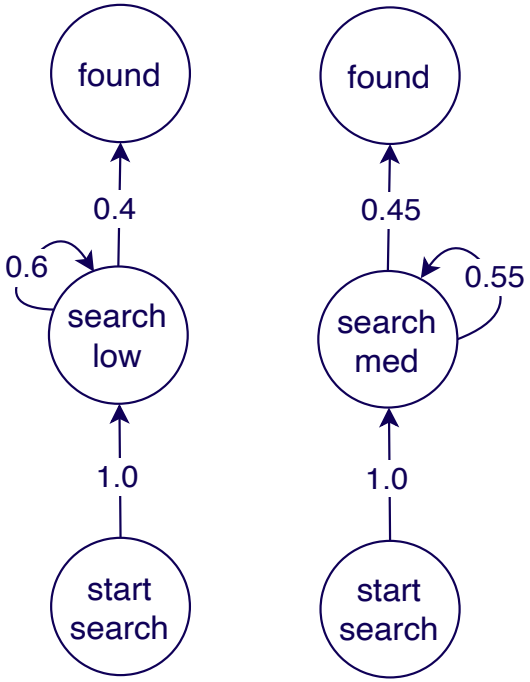




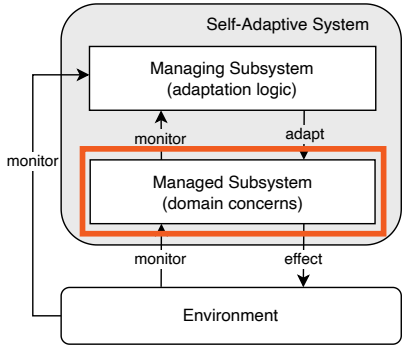
Feature Model

(Configurations of managed subsystem)

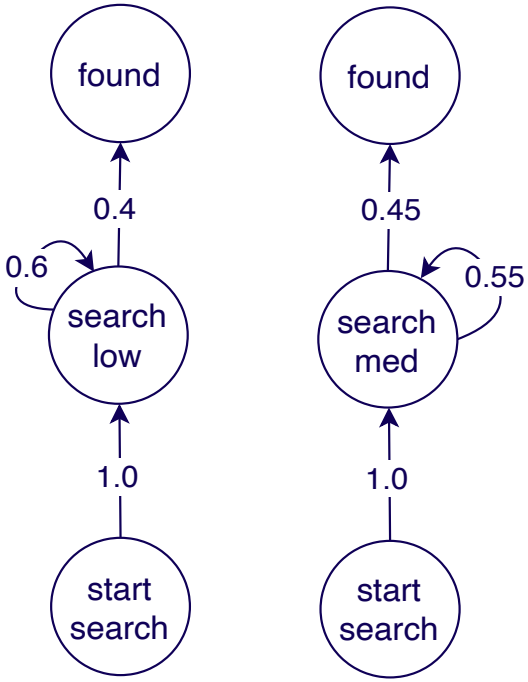
Managed Subsystem: Behaviour



Configuration:
Markov Chain



Managed Subsystem: Behaviour



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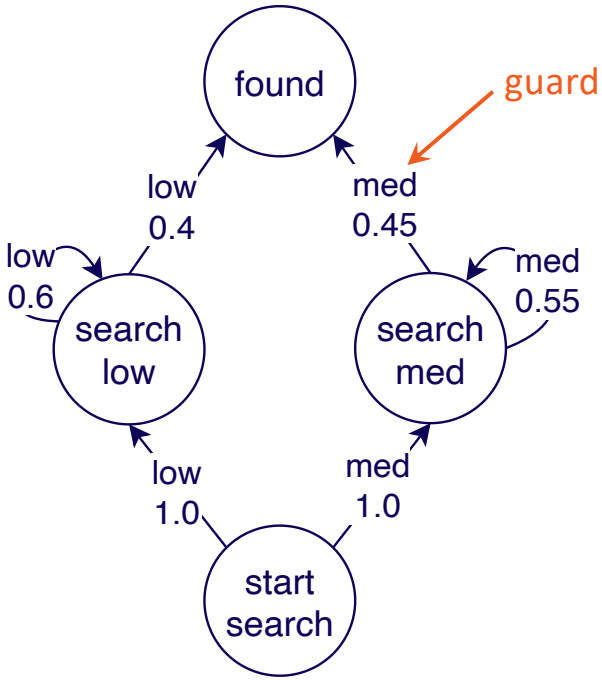
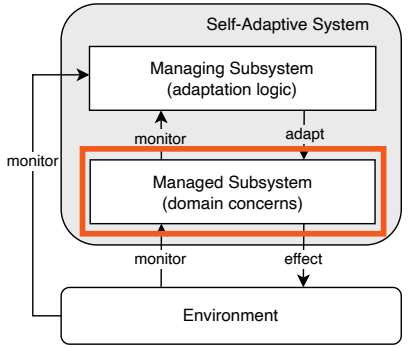
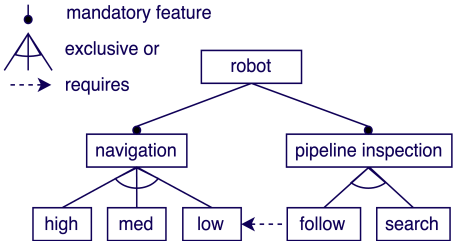


All configurations: *Featured*
Markov Chain (variant of FTS)





Feature Model

A. Classen, M. Cordy, P.-Y. Schobbens, et al., FTS: Foundations for Verifying Variability-Intensive Systems and Their Application to LTL Model Checking. IEEE TSE, 2013.

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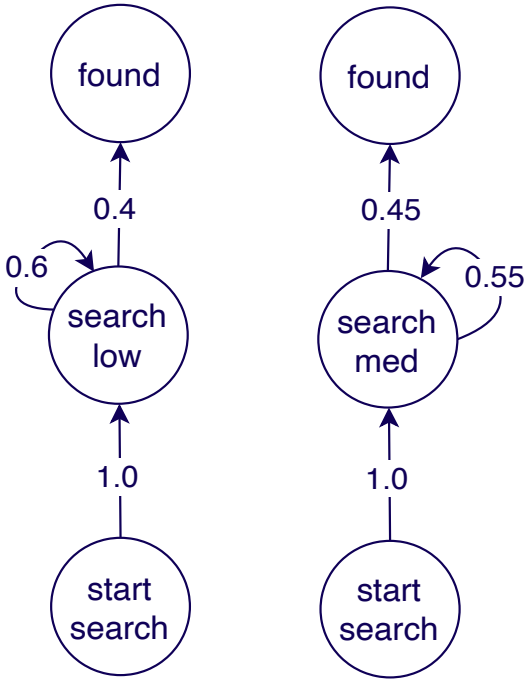

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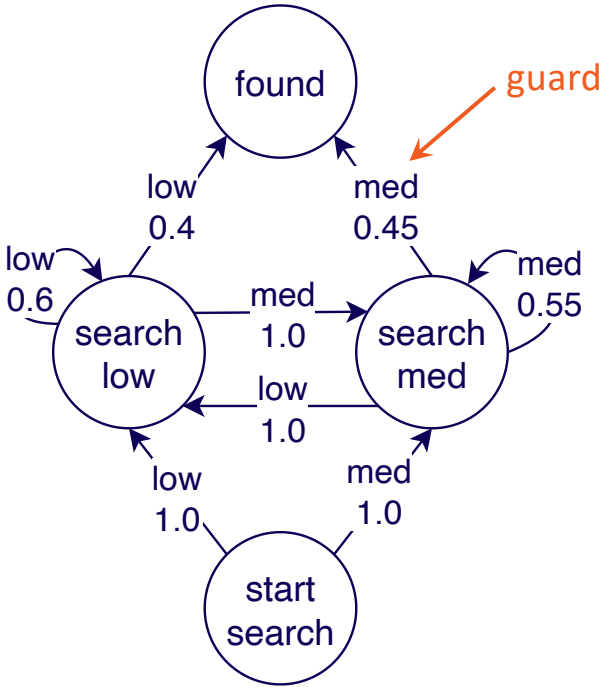

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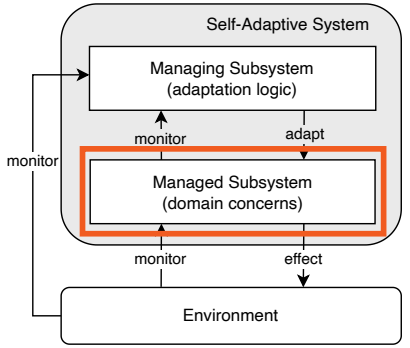

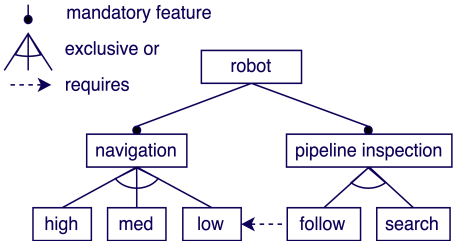

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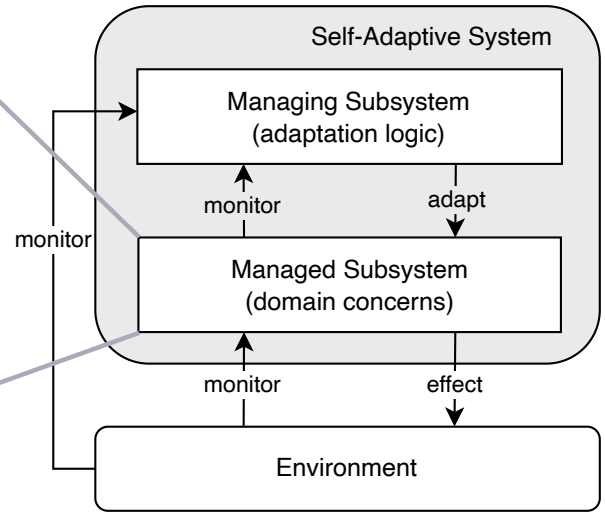
Modelling

Feature Model
+
Probabilistic
Featured Transition System

Software Product Line



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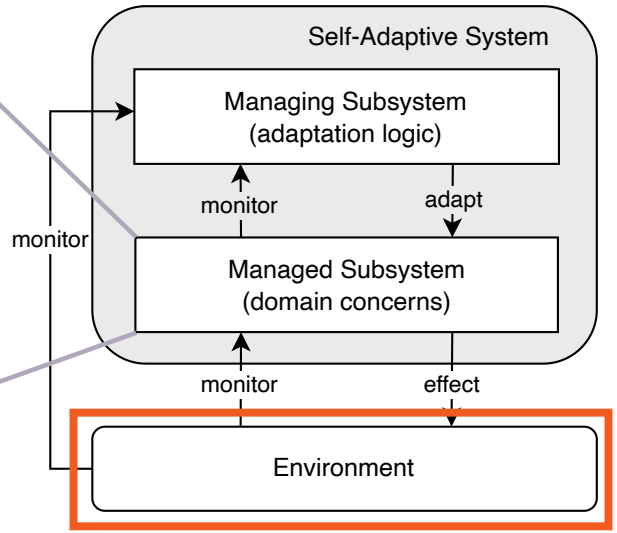
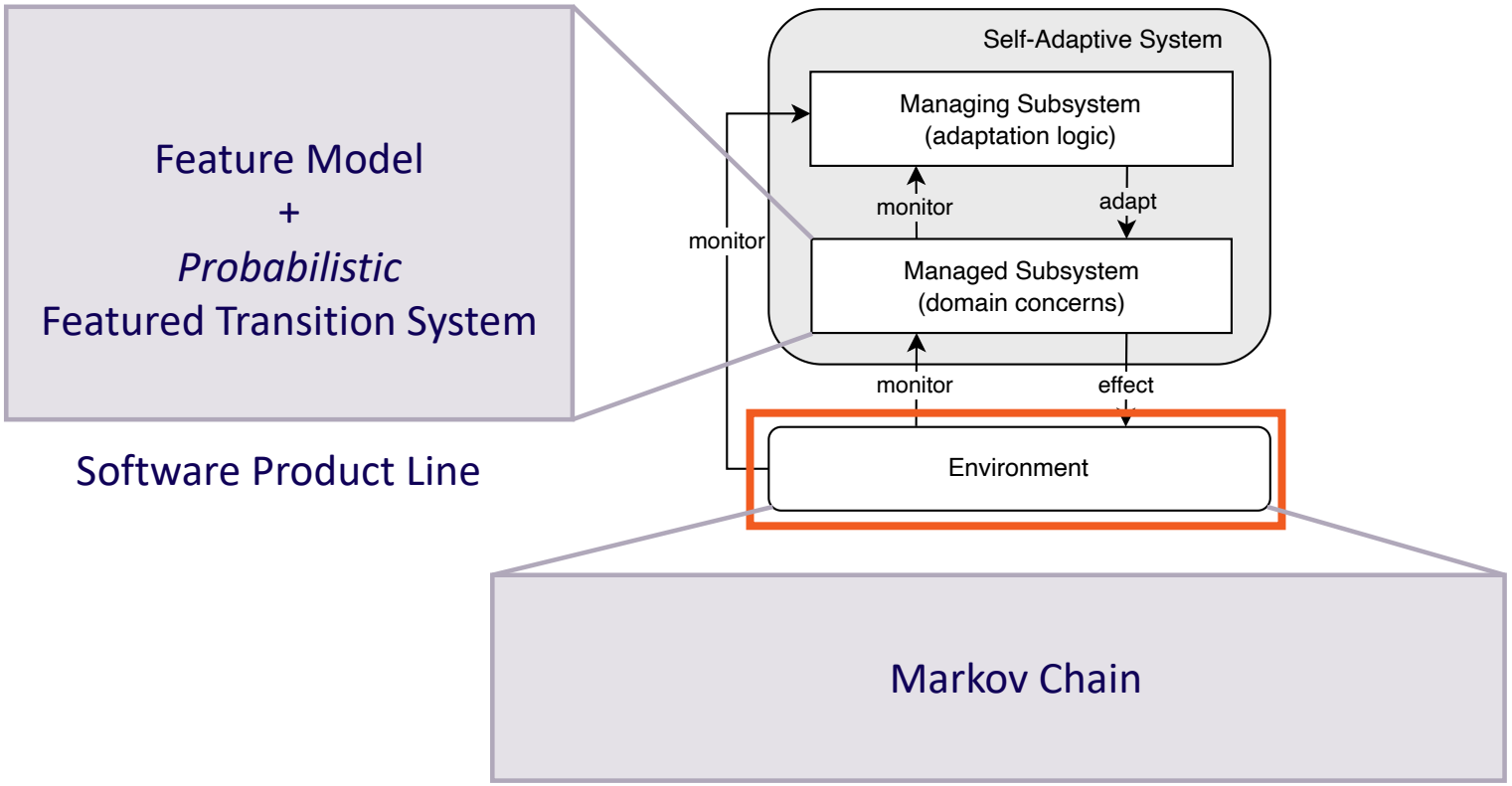
Software Product Line



Modelling


Feature Model
+
Probabilistic
Featured Transition System
Software Product Line
Self-Adaptive System
Managing Subsystem
(adaptation logic)
monitor
adapt
monitor
Managed Subsystem
(domain concerns)
monitor
effect
Environment
Markov Chain

Modelling

Feature Model
+
Probabilistic
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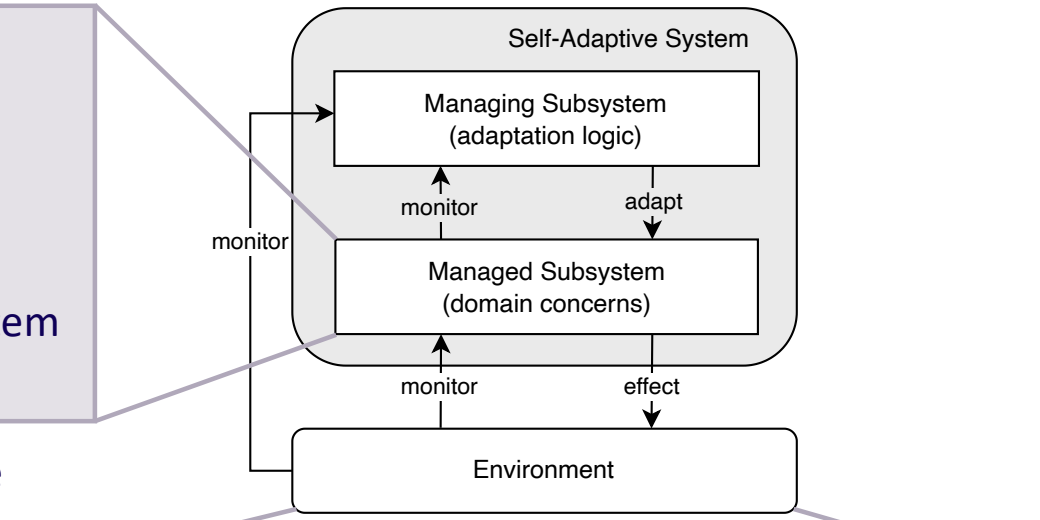
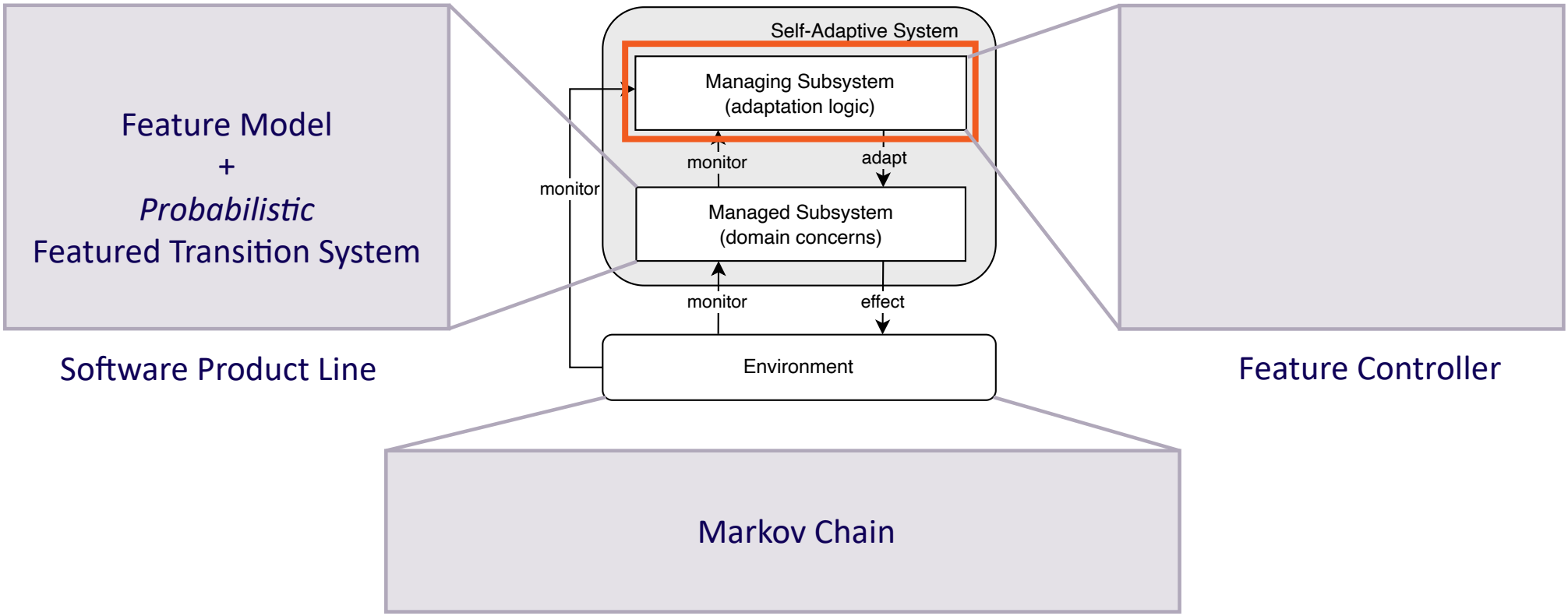
Software Product Line



Markov Chain

Modelling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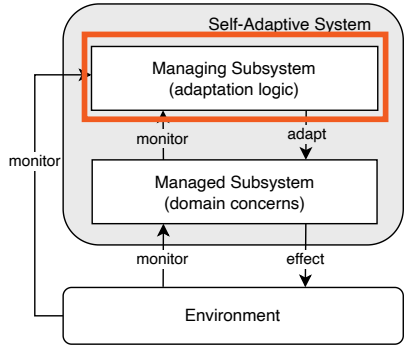
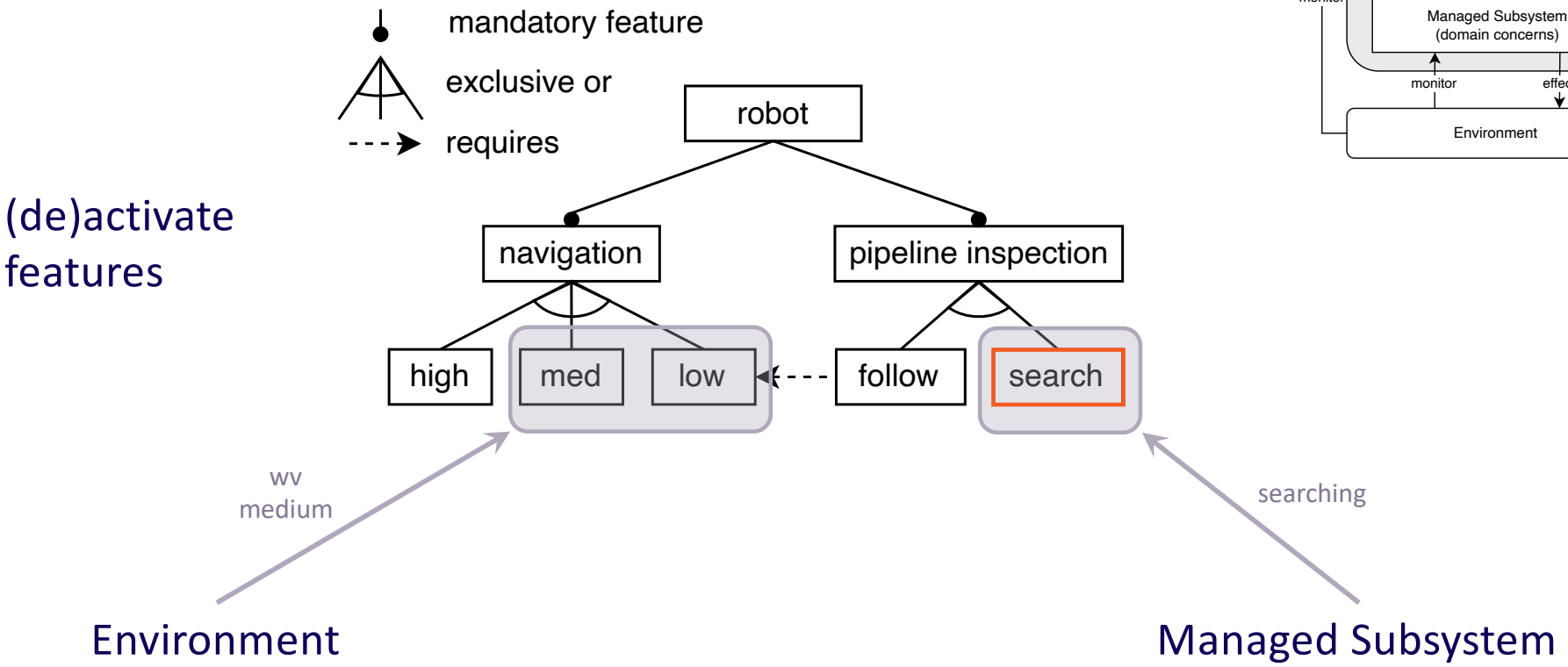
Environment
Feature Controller
Markov Chain

Managing Subsystem I





Managing Subsystem II

```
[step] (s!=found) & active(search) & water_visib = medium
            -> activate(low) & deactivate(med) & deactivate(high);
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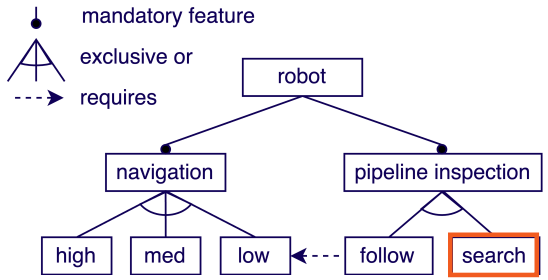

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```
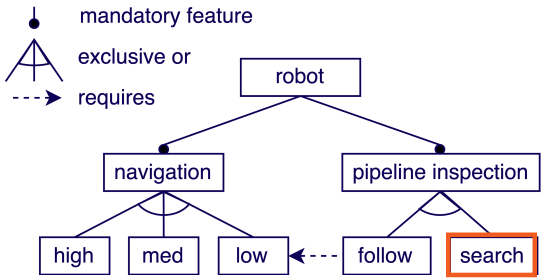

Managing Subsystem II

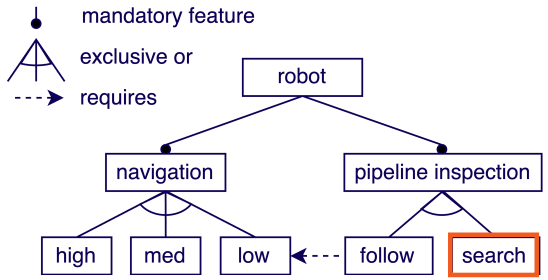


Managed Subsystem

Environment

```
[step] (s!=found) & active(search) & water_visib = medium
          -> activate(low) & deactivate(med) & deactivate(high);
```

Managing Subsystem II

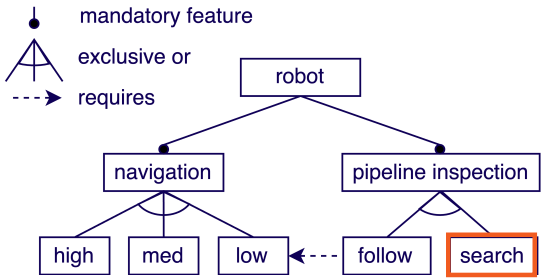


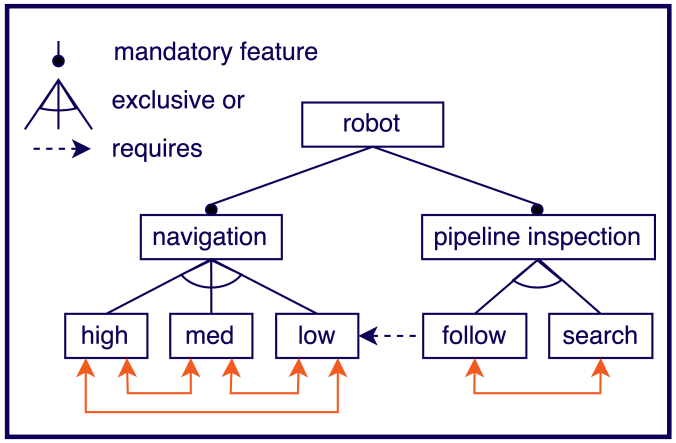
Managed Subsystem

Environment

```
[step] (s!=found) & active(search) & water_visib = medium
            -> activate(low) & deactivate(med) & deactivate(high);

[step] (s!=found) & active(search) & water_visib = medium
            -> activate(med) & deactivate(low) & deactivate(high);
```

Managing Subsystem II



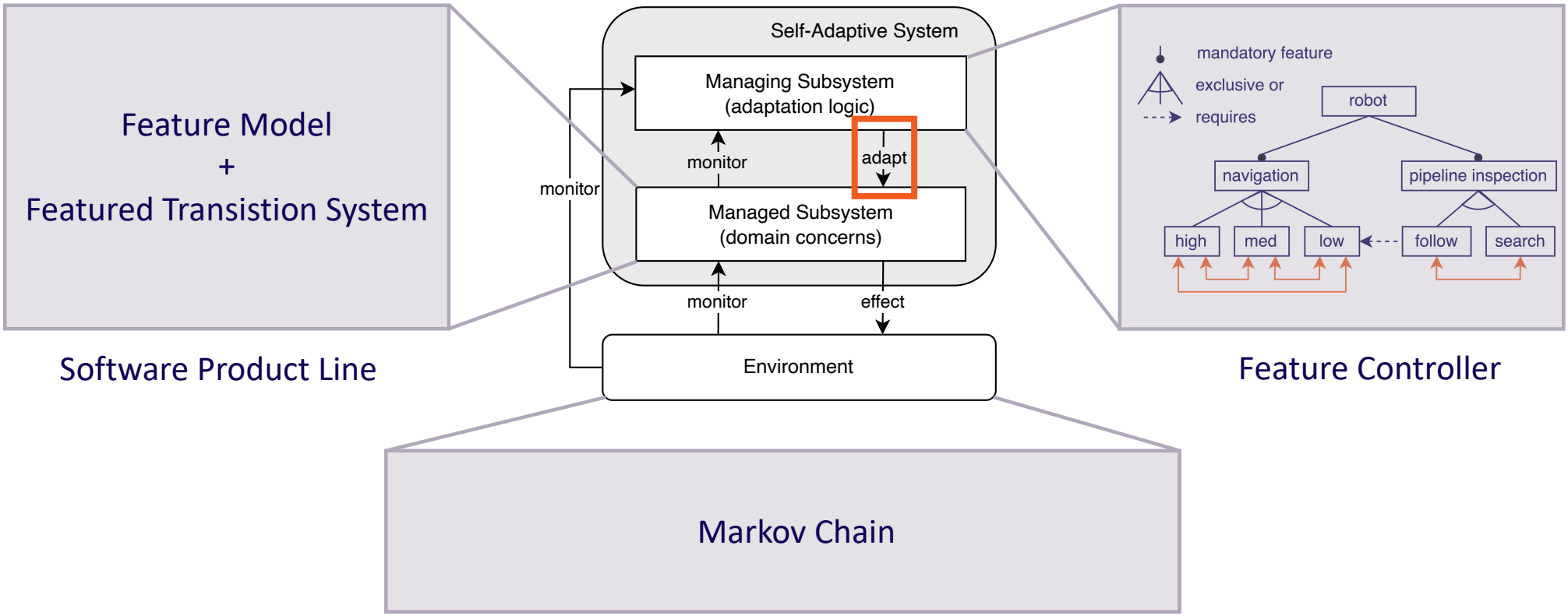


Managed Subsystem

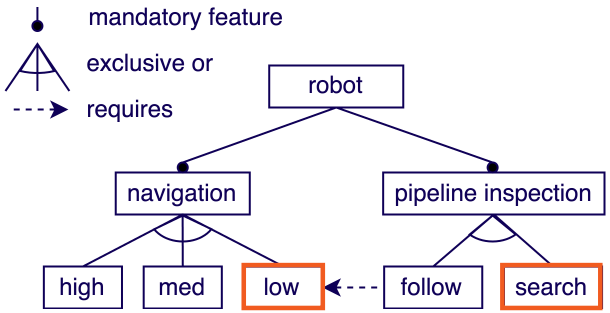
Environment

```
[step] (s!=found) & active(search) & water_visib = medium
            -> activate(low) & deactivate(med) & deactivate(high);

[step] (s!=found) & active(search) & water_visib = medium
            -> activate(med) & deactivate(low) & deactivate(high);
```

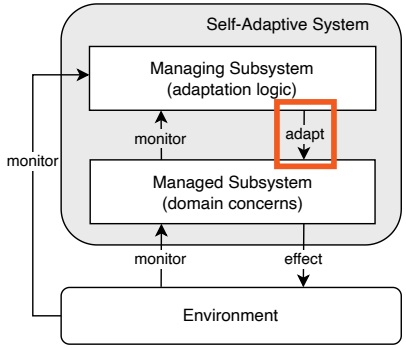
Modelling

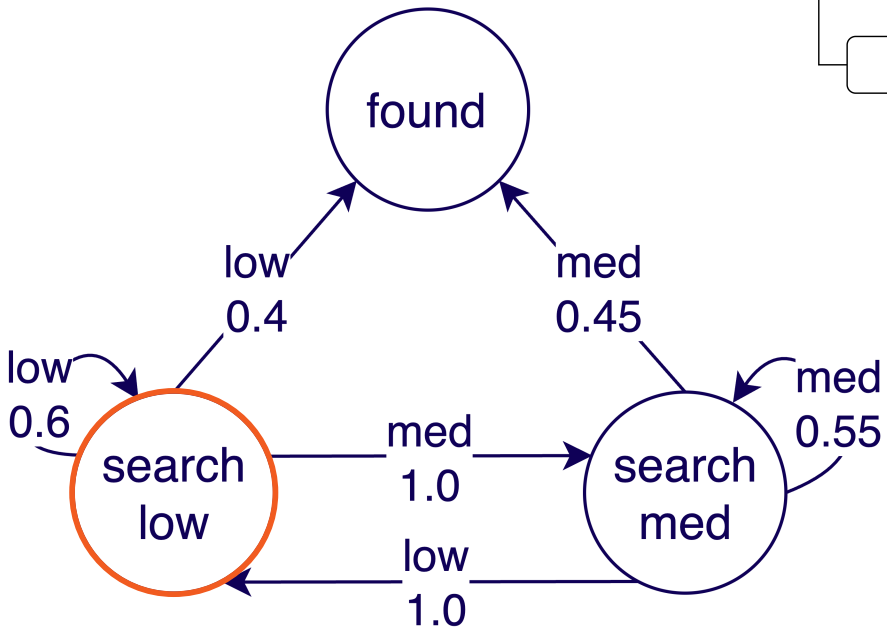

Feature Model
+
Featured Transistion System
Software Product Line
Self-Adaptive System
Managing Subsystem
(adaptation logic)
monitor
adapt
monitor
Managed Subsystem
(domain concerns)
monitor
effect
Environment
mandatory feature
exclusive or
requires
robot
navigation
pipeline inspection
high
med
low
follow
search
Feature Controller
Markov Chain

Adaptation



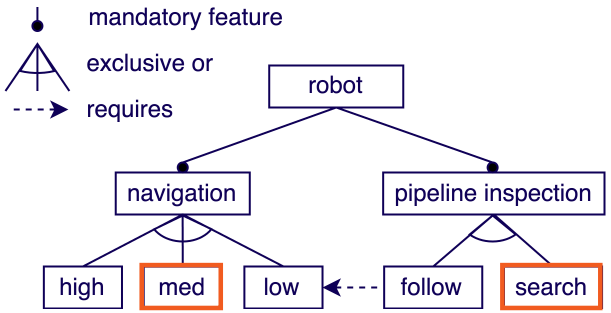
Managing Subsystem



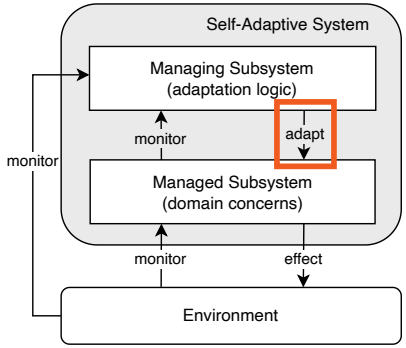


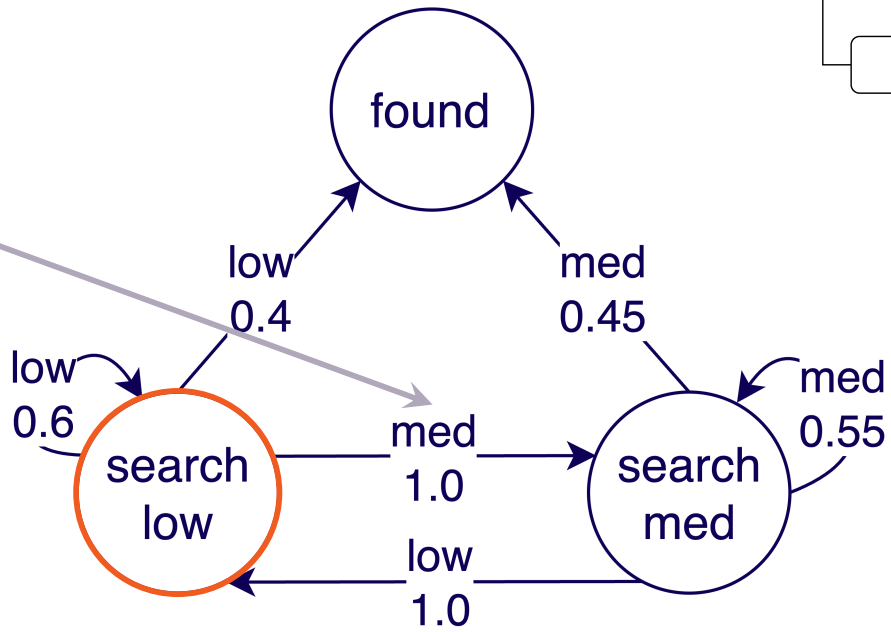
Managed Subsystem

Adaptation



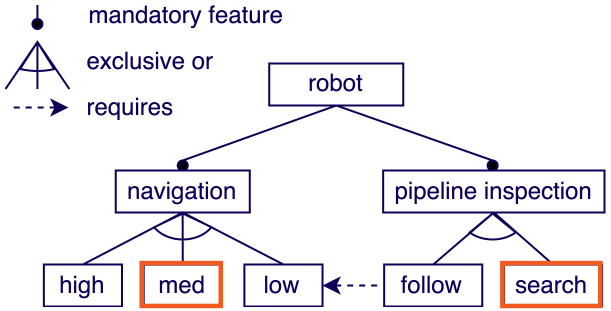
Managing Subsystem



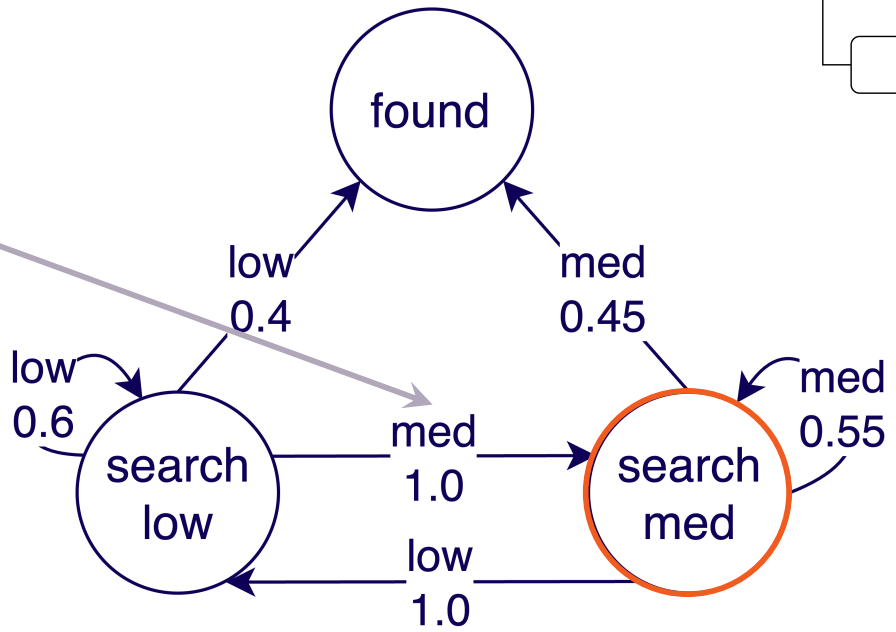


Managed Subsystem

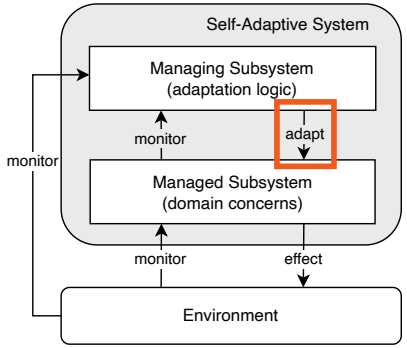
Adaptation



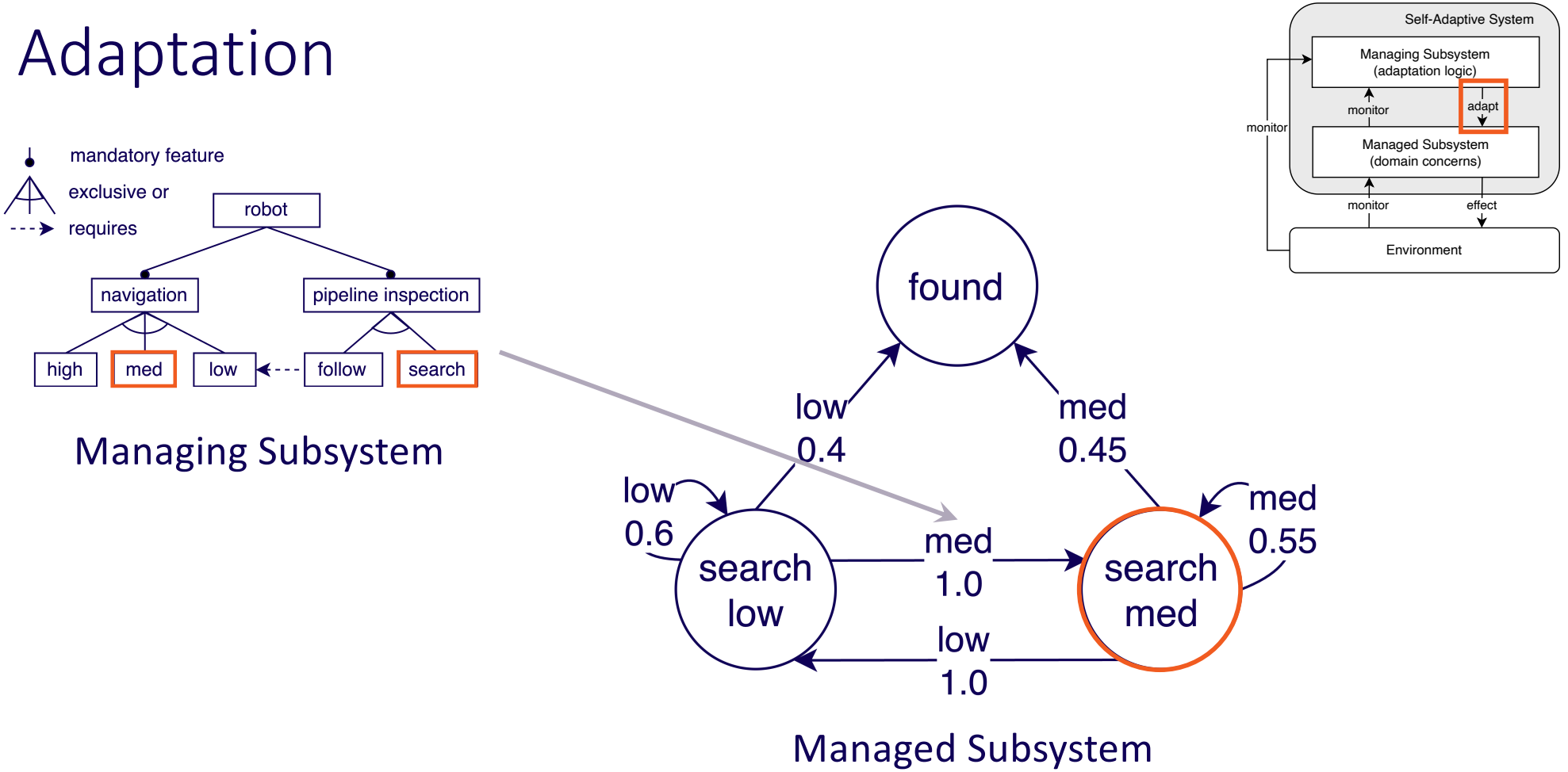
Managing Subsystem



Managed Subsystem



Adaptation



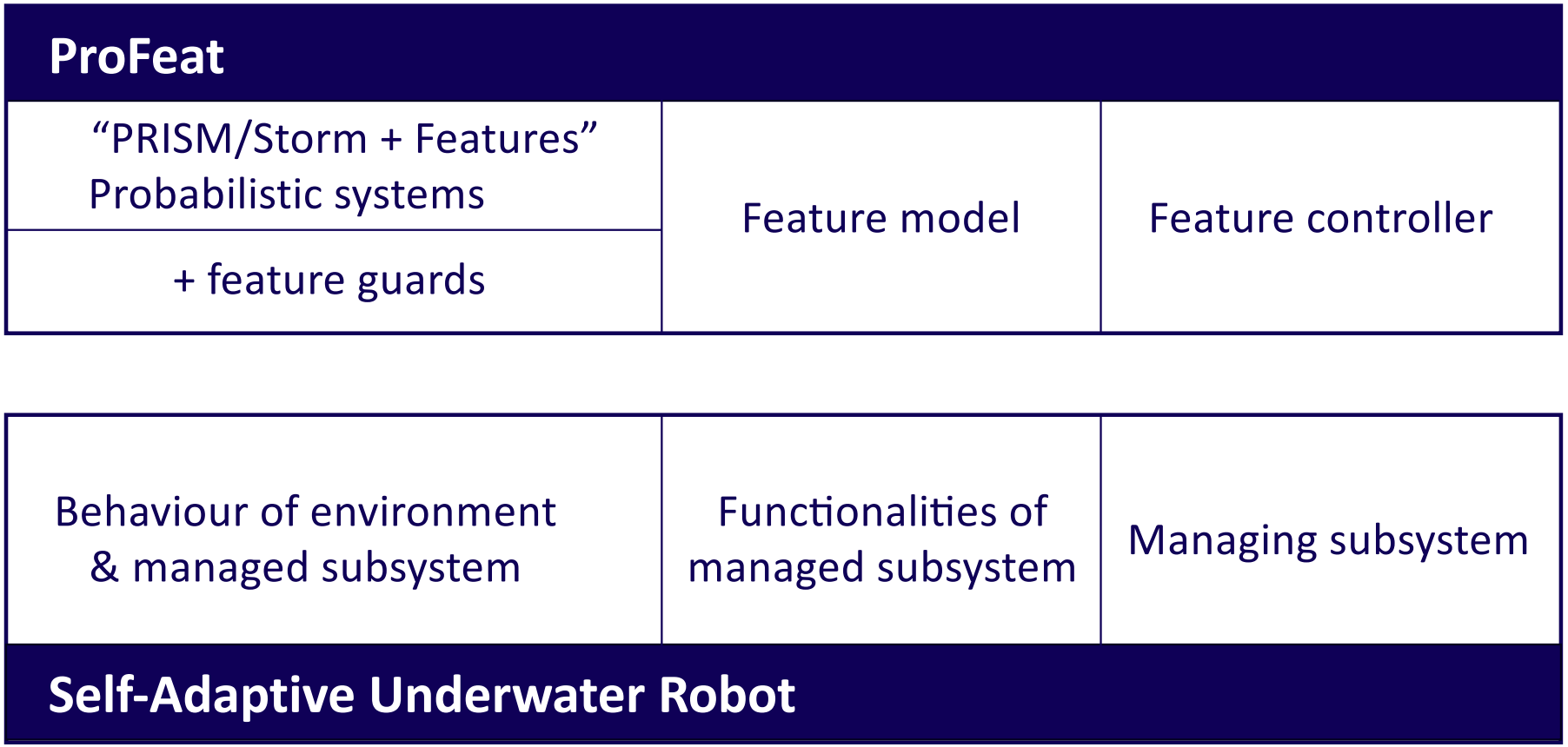

```
[step] (s=search_low & active(low)) -> 0.4:(s'=found) + 0.6: (s'=search_low);
```

ProFeat: feature-aware probabilistic model checker

<table>
<tr><th colspan="3">ProFeat</th></tr>
<tr><td>“PRISM/Storm + Features”
Probabilistic systems</td><td rowspan="2">Feature model</td><td rowspan="2">Feature controller</td></tr>
<tr><td>+ feature guards</td></tr>
</table>

P. Chrszon, C. Dubslaf, S. Klüppelholz, C. Baier, ProFeat: Feature-Oriented Engineering for Family-Based Probabilistic Model Checking. ACM FAC, 2018.

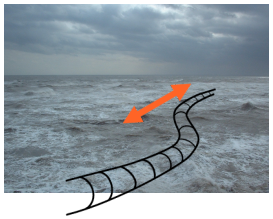
ProFeat: feature-aware probabilistic model checker



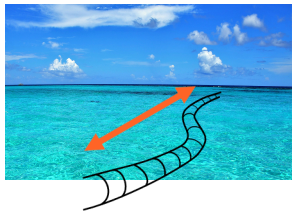
P. Chrszon, C. Dubslaf, S. Klüppelholz, C. Baier, ProFeat: Feature-Oriented Engineering for Family-Based Probabilistic Model Checking. ACM FAC, 2018.

ProFeat: Family-based Analysis (Safety)

North Sea



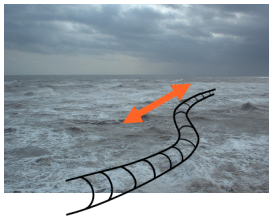
Caribbean Sea



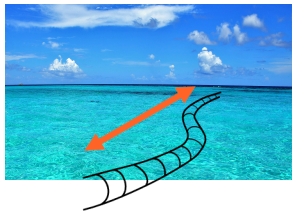
[North Sea] https://msittig.freeshell.org/imgs/wallpaper/msg_data/North%20Sea.jpg.html
[Caribbean Sea] https://www.travelweekly.com/Caribbean-Travel/Hurricanes-slow-down-a-gainful-year-for-Caribbean-tourism

ProFeat: Family-based Analysis (Safety)

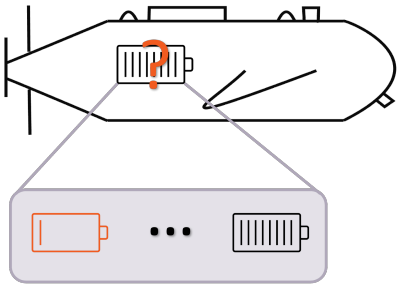
North Sea



Caribbean Sea



Expected Cost

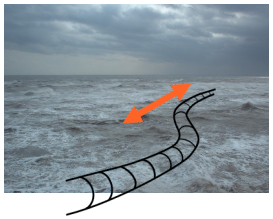


```
R{“energy”}min=? [F s=done]
```

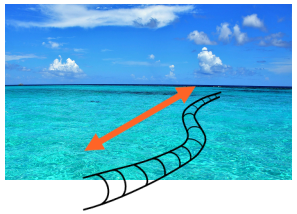
[North Sea] https://msittig.freeshell.org/imgs/wallpaper/msg_data/North%20Sea.jpg.html
[Caribbean Sea] https://www.travelweekly.com/Caribbean-Travel/Hurricanes-slow-down-a-gainful-year-for-Caribbean-tourism

ProFeat: Family-based Analysis (Safety)

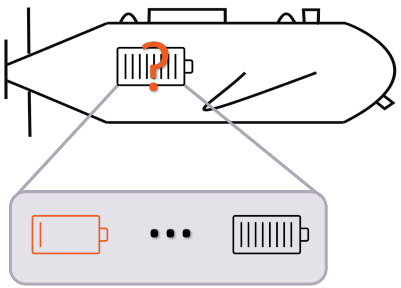
North Sea



Caribbean Sea

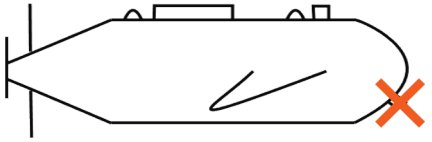


Expected Cost



R{“energy”}min=? [F s=done]

Sensor Failures

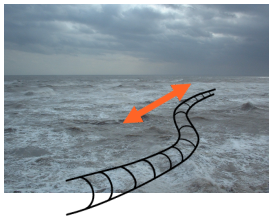


Pmin=? [!sonar_failed U s=done]

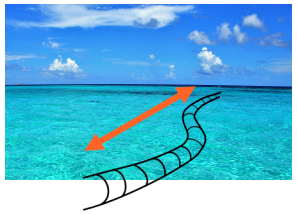
[North Sea] https://msittig.freeshell.org/imgs/wallpaper/msg_data/North%20Sea.jpg.html
[Caribbean Sea] https://www.travelweekly.com/Caribbean-Travel/Hurricanes-slow-down-a-gainful-year-for-Caribbean-tourism

ProFeat: Family-based Analysis (Reliability)

North Sea



Caribbean Sea



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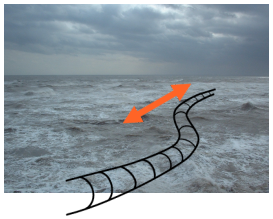
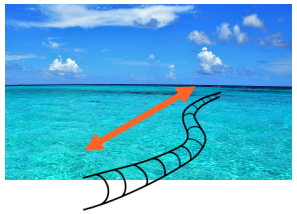
[Caribbean Sea] https://www.travelweekly.com/Caribbean-Travel/Hurricanes-slow-down-a-gainful-year-for-Caribbean-tourism

ProFeat: Family-based Analysis (Reliability)

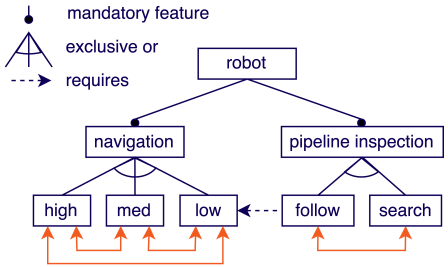
North Sea



Caribbean Sea



Correctness Adaptation Logic

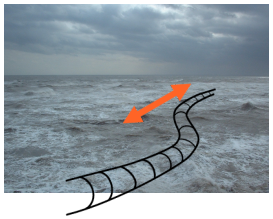



```
P>=1.0 [G ((active(search) & wv<med_visib)
       => (F active(low) | wv>=med_visib)]
```

[North Sea] https://msittig.freeshell.org/imgs/wallpaper/msg_data/North%20Sea.jpg.html
[Caribbean Sea] https://www.travelweekly.com/Caribbean-Travel/Hurricanes-slow-down-a-gainful-year-for-Caribbean-tourism

ProFeat: Family-based Analysis (Reliability)

North Sea



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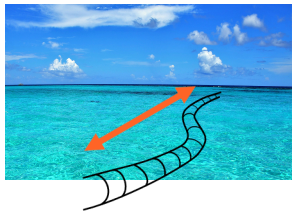
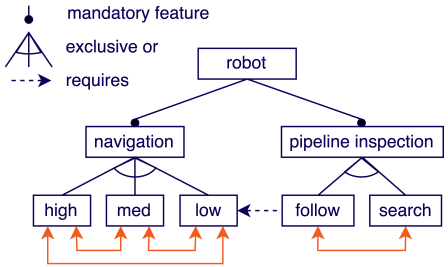
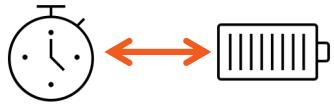


Correctness Adaptation Logic




```
P>=1.0 [G ((active(search) & wv<med_visib)
       => (F active(low) | wv>=med_visib)]
```

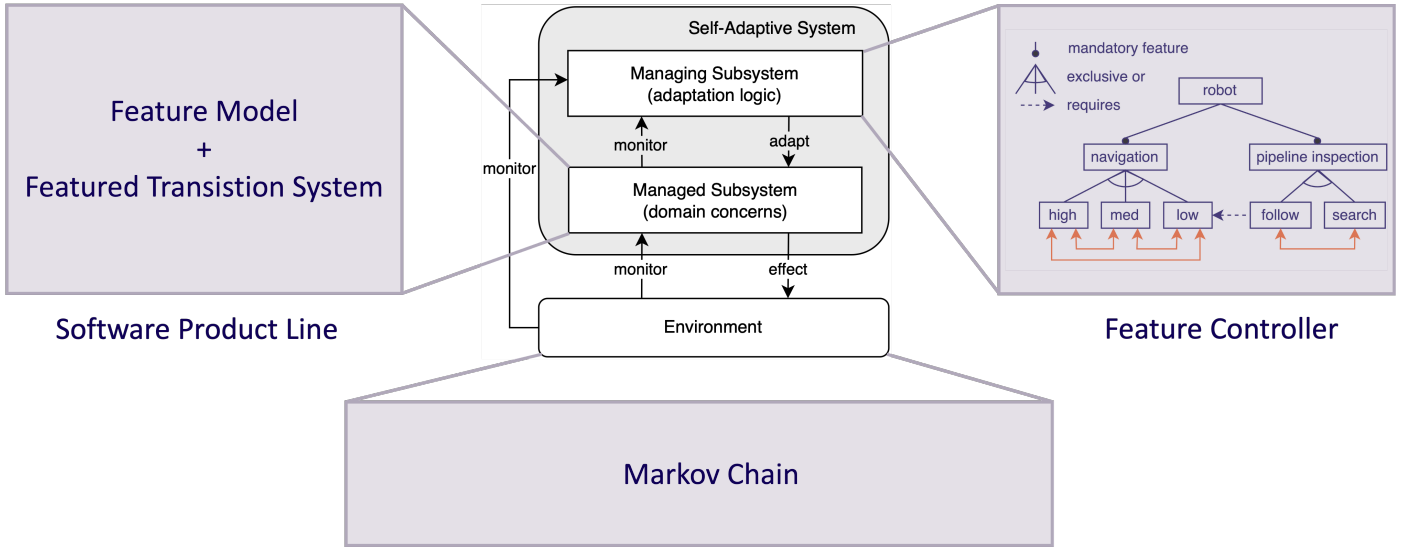
Trade-Offs



```
multi(R{"time"}min=?, R{"energy"}min=?
[F s=done])
```

[North Sea] https://msittig.freeshell.org/imgs/wallpaper/msg_data/North%20Sea.jpg.html
[Caribbean Sea] https://www.travelweekly.com/Caribbean-Travel/Hurricanes-slow-down-a-gainful-year-for-Caribbean-tourism

Showed how to Model and Analyse SASs with SPL Techniques



+

Family-based Probabilistic Model Checking