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MANAGING VARIABILITY AND EVOLUTION IN HIGH-TECH EQUIPMENT

FOSD 2024 Keynote

Prof. dr. Benny Akesson

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KEY MESSAGES

This presentation has four key messages:

1. System complexity trends for high-tech equipment

2. TNO-ESI and its role in the high-tech industry

3. Finished industry case:
   Specification, verification, and adaptation of software interfaces

4. Ongoing industry case:
   Variability and evolution in software platforms

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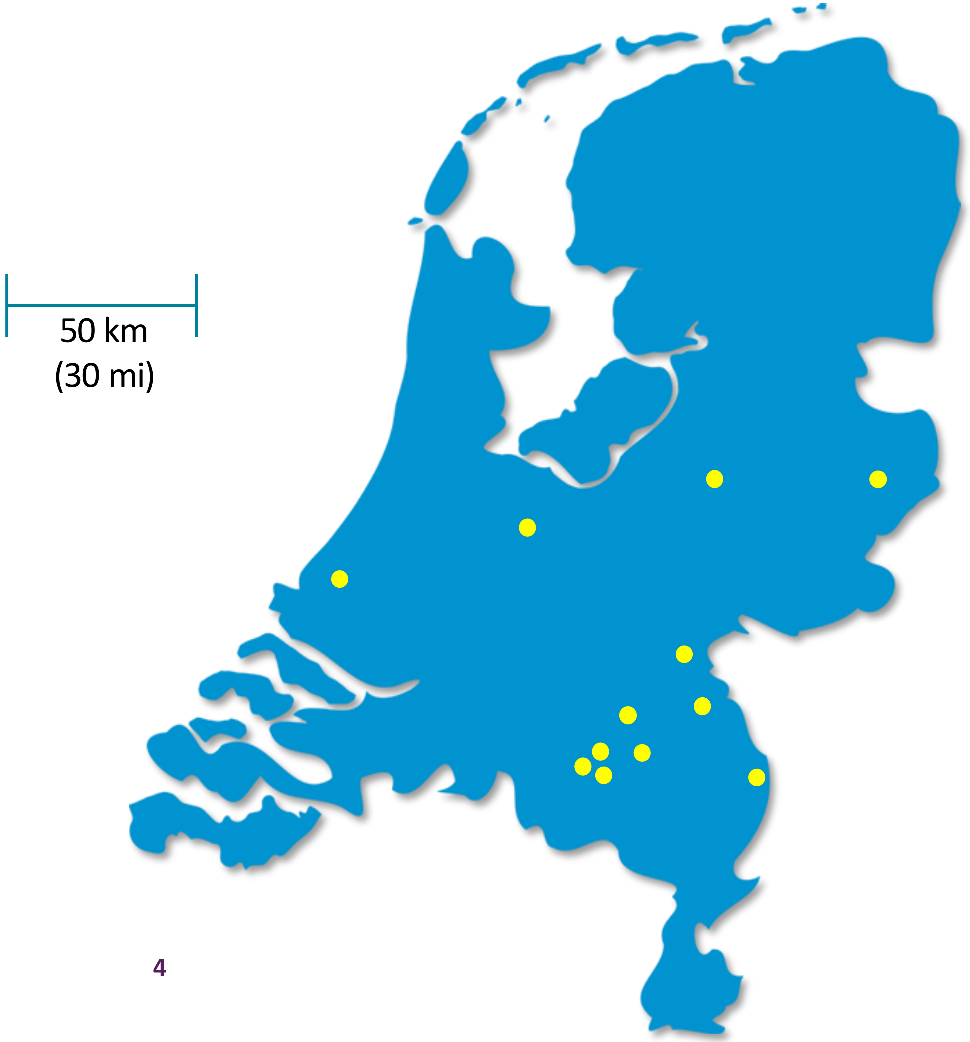
EXAMPLES OF DUTCH HIGH-TECH SYSTEMS



SYSTEM COMPLEXITY IS INCREASING!

- Five technological and market trends drive increasing complexity in high-tech systems:

1. **Additional functionality**
   - Number of interfaces and lines of code are **rapidly increasing**
2. **Mass customization**
   - Increased customization of systems at design time to the point where **each system is unique**
3. **Long life times**
   - Systems operate for decades and need to **continuously evolve** after deployment
4. **Increasing autonomy**
   - Systems acting autonomously with **little or no human interaction**
5. **Systems of systems**
   - Interconnected systems of which **nobody is in complete control**

MANAGING COMPLEXITY

- Managing complexity in high-tech systems is critical to successful development and deployment
  - Impacts all phases of development: **design**, **implementation**, **verification**, and **evolution**

- Increasing complexity cannot be dealt with by current engineering methodologies
  - Increasing **development and maintenance costs**
  - Increasingly hard to **guarantee functional correctness** and **balance system qualities**
  - Severe shortage of **skilled people**

- **New design methodologies** are required to manage the increasing complexity and enable future generations of systems to be developed efficiently!

- ESI is an organization that **orchestrates** the **innovation chain** for design methodologies in the Dutch high-tech eco-system and conducts **applied research to improve industrial practice**

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TNO-ESI AT A GLANCE

SYNOPSIS

- Foundation ESI started in 2002
- ESI acquired by TNO per January 2013
- ~60 staff members many with extensive industrial experience
- 8 part-time professors

FOCUS

Managing complexity of high-tech systems

through

- system architecting
- system reasoning and
- model-driven engineering

delivering

- methodologies validated in cutting-edge industrial practice

PARTNER BOARD

ASML, Canon – Canon Production Printing, itec – equipment + automation tech, Philips, Radboud University Nijmegen, Thales – Building a future we can all trust, TNO, TU Delft, TU/e Eindhoven University of Technology, University of Twente, University of Amsterdam, Vanderlande

Capgemini engineering, Strypes

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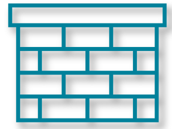
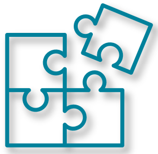
ABC OF COMPLEXITY MANAGEMENT

A. **Abstraction**: Identify high-level concepts that hide low-level details
   - Software is programmed in high-level programming languages and not using machine code



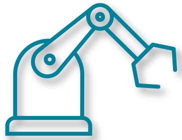
B. **Boundedness**: Impose acceptable restrictions on the considered problem space
   - Constraints on environment in which system has to function correctly

C. **Composition**: Divide one problem into multiple independent smaller problems
   - System is decomposed into logical functions that are developed individually



Automation is key to coping with complexity

- Not a fundamental technique to reduce complexity, rather about **productivity**



MANAGING COMPLEXITY WITH MODELS

- **Model-based methodologies** are promising for managing complexity

- There is a clear relation to the ABC Complexity Management Techniques
  - Models are **abstractions** of the system
  - System **boundedness** can be expressed through parameter ranges and constraints in models
  - Systems are (de-)composed into models covering different parts or aspects.
    Model-based development methodologies are the **composition** of these

- The formal nature of models provide a strong link to **automation**
  - Models are used as a **source** for automated **analysis** and **synthesis**

2

SPECIFICATION, VERIFICATION, AND ADAPTATION OF SOFTWARE INTERFACES

2019-2021

MOTIVATION

- Thales systems have life time > 30 years and require upgrades
  - Both technology and customer requirements **significantly change** during life time
  - Compute nodes need to be added or replaced to **counter obsolescence** or **improve performance**
  - **New software with new capabilities** becomes available

- System upgrades can take 1-2 years and happen every 10-15 years
  - Many small updates collected into **big infrequent upgrades**
  - System **evolves slowly** and in big steps, increasing risk

- Systems need to continuously evolve to **reduce risk** and **increase added value**

MODULARITY IN SOFTWARE ARCHITECTURES

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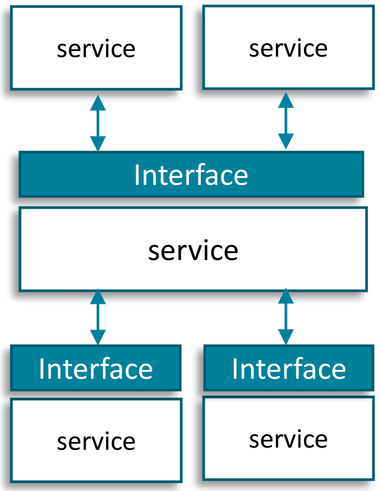
- Increasing software complexity is tackled by **modularization**
    - Software is **decomposed** into **services** corresponding to particular functionality **(composition)**
    - **Asynchronous communication** often used to achieve **loose coupling** between services
    - **Abstraction** of service implementation and technology is provided by an **interface**

- Modularity addresses the stated complexity drivers
    - Improved **scalability**, **customization**, and **evolvability**



PROBLEM STATEMENT

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1. Many asynchronously communicating services lead to an explosion of possible behaviors
    - Interactions between services become **very hard to verify**
    - **Early design errors** are detected much later in the system life-cycle, **increasing cost**
2. Updating interfaces becomes prohibitive
    - **Manually changing an interface is quick**, but **updating many incompatible services takes time**
    - Evolving interfaces is hence **expensive** and **time consuming**, resulting in **technical debt**

METHODOLOGY OVERVIEW

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- Six-step Methodology
  1. **Specify structure and behavior of interfaces** using **ComMA**
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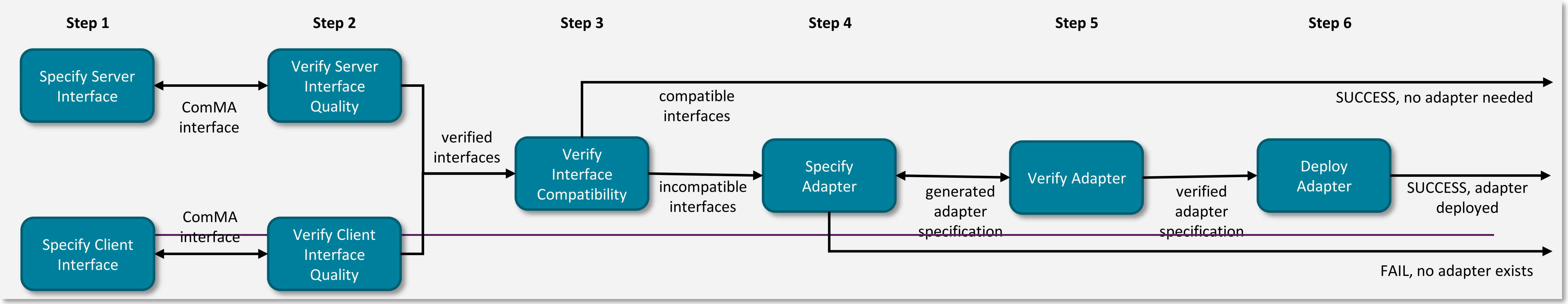

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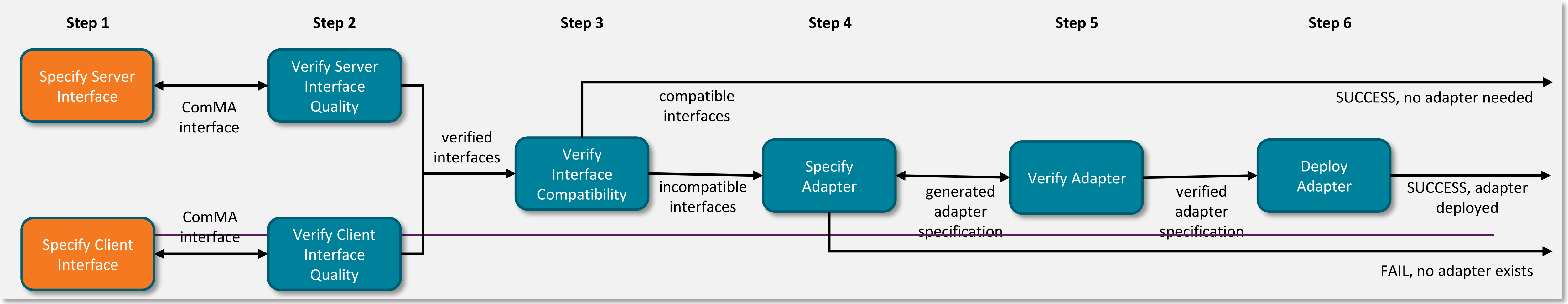


INTERFACE SPECIFICATION

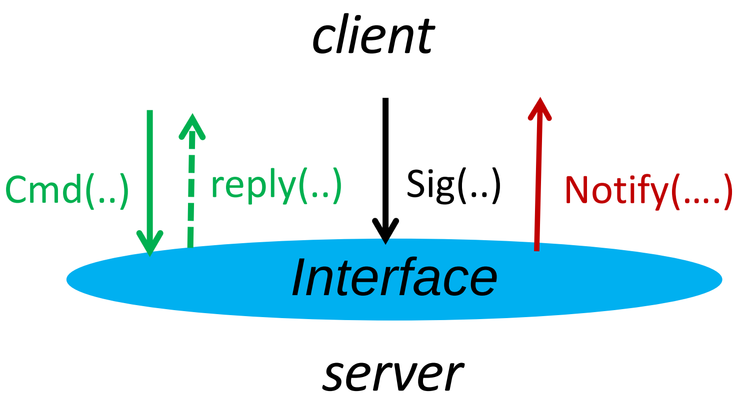
- ComMA was selected as specification language for six good reasons
    1. **We did not want to reinvent the wheel** by making a new interface specification language
    2. specifies **both structure and behavior**, required to validate both aspects of compatibility
    3. models **both synchronous and asynchronous** communication
    4. **automatic inference** and **migration** of interface specifications simplifies industrial adoption
    5. the tooling is based on **Eclipse**, which is one of the most commonly used modeling tools in the embedded domain
    6. developed and **successfully applied in industry**

Web: https://projects.eclipse.org/projects/technology.comma

ABOUT ECLIPSE COMMASUITE

Domain Specific Language (DSL) to express client-server interface:

- **Signature**
  - Commands: synchronous function calls - from client to server
  - Signals: asynchronous function calls - from client to server
  - Notifications: asynchronous notifications - from server to client(s)
- **Behavior** by **protocol state machine**
  - Contract between client(s) and server; allowed sequences of events
  - Non-determinism allowed
- Supports both **data constraints** and **timing constraints**



BIGGER PICTURE WITH COMMA

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Model Inference

Structure

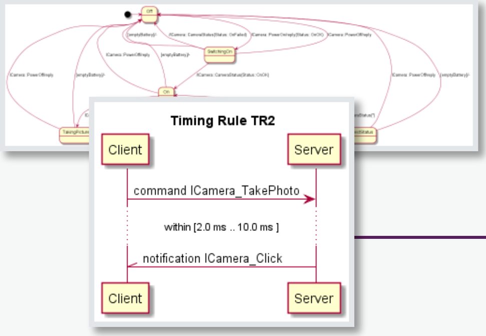
```
commands
    Status PowerOn
    void   PowerOff
    bool Zoom(in real factor,
              out real result,
              out real scale
    )
    Picture TakePhoto(Time t)
    int  GetPictureNumber
signals
    ProvideStatus
notifications
    CameraStatus(Status s)
    Click
}
```

Behavior

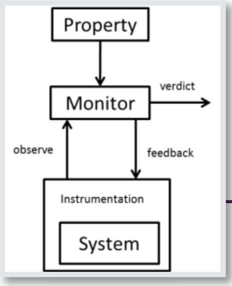
```
initial state Off {
    transition trigger: ICamera::PowerOn
        do: reply(Status::OnOK)          next state: SwitchingOn
        OR
        do: reply(Status::OnFailed)      next state: Off
}
state SwitchingOn {
    transition do: ICamera::CameraStatus(Status::OnOK)
                                                next state: On

    transition do: ICamera::CameraStatus(Status::OnFailed)
                                                next state: Off
}
```

Generated

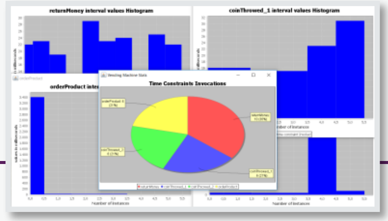
Visualization



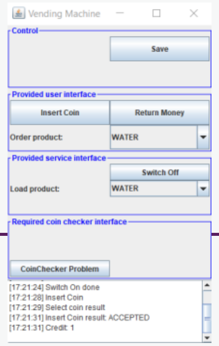
Monitoring



Statistics



Simulation



Documentation

METHODOLOGY OVERVIEW

- Six-step Methodology

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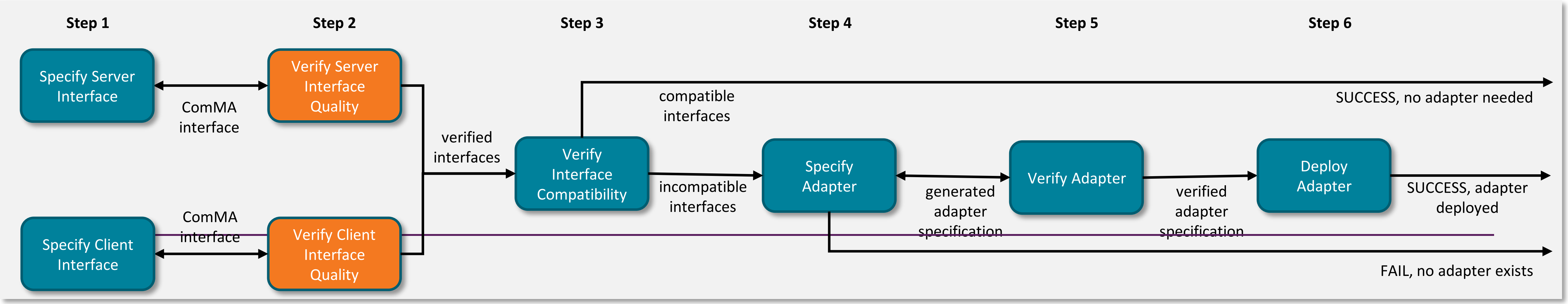

REACHABILITY GRAPH

- Verification of ComMA specification possible by translation into **Colored Petri Net (CPN)** model

- State of a CPN model
  - **Full state** is the **marking** + **values of all variables**
  - **Initial full state** is **initial marking** + **initial values of all variables**

- A **reachability graph** is generated from the CPN model
  - Considers **all paths** from the initial full state for a given set of input data

MODEL QUALITY CHECK

- Reachability graphs model quality checking using reachability analysis
  - Allows **state and transition coverage** of interface to be determined
  - Enables **unreachable states**, **deadlocks**, **livelocks**, and **sink states** in server state machine to be detected
  - Also **race conditions**, **property violations**, and **confusion** in interactions with a **mirrored client**

- User gets feedback on model quality from a dashboard
  - **Lists** and **visualizes** quality issues and provides **guidelines** for how to resolve them

IMPRESSION OF MODEL QUALITY DASHBOARD

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Statistics

Reachability Graph Coverage:	Full [4 states]
Transition Coverage:	100.0%
State Coverage:	100.0%
Num Of States:	4

Summary

Interface

Server State Machine

- Deadlocks (0)
- Livelocks (0)
- Unreachable States (0)
- Sink States (0)

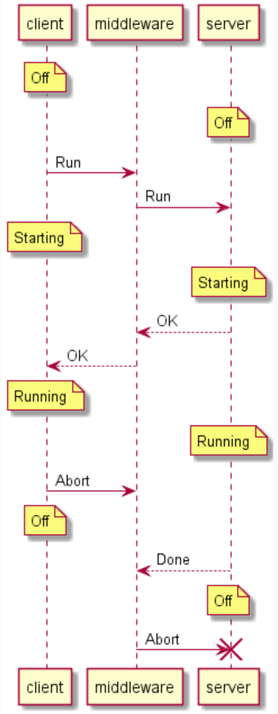
Client Communication

- Choice Properties (2)
- Leg Properties (7)
- Service Race Conditions (1)
- Client Race Conditions (0)
- Simple Confusions (0)

Verification Results of ComMA Interface

ServerRaceConditions

Race Condition in State: Running



Resolution: When server emits notifications : Done - Signal Abort is missing in state Off

```
import "Example.signature"

interface Example version "1.0"

machine StateMachine {

        initial state Off {
                transition trigger: Run next state: Starting
                transition do: Done next state: Off
        }

        state Starting {
                transition do: OK next state: Running
                transition do: Done next state: Off
        }

        state Running {
                transition do: Done next state: Off
                transition trigger: Run next state: Rejecting
                transition trigger: Abort next state: Off
        }

        state Rejecting {
                transition do: NOT_ALLOWED next state: Running
                transition do: Done next state: Off
        }
}
.ÓMÝ
```

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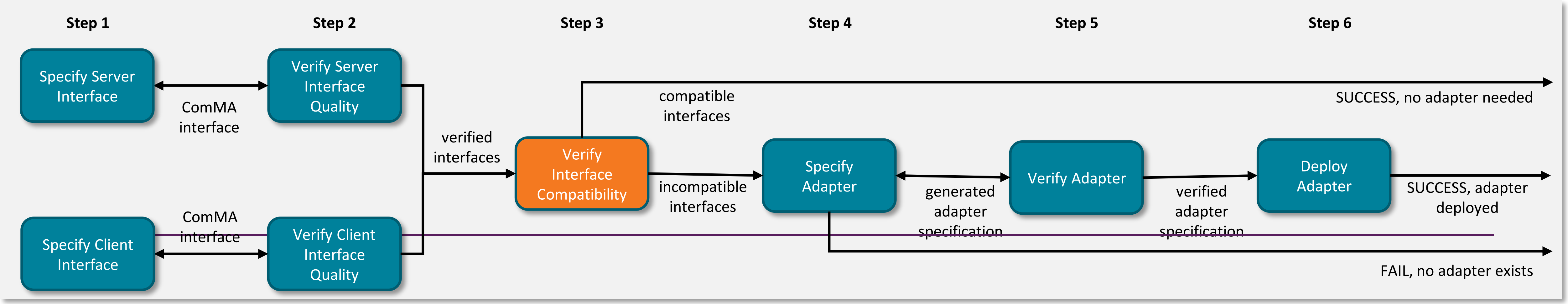
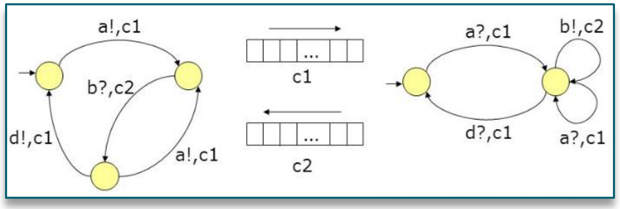
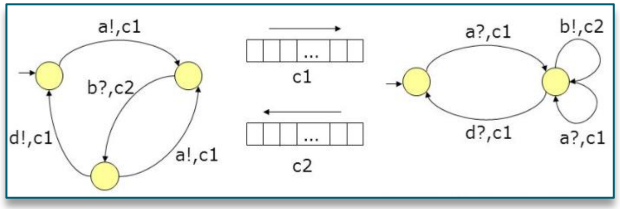


Client ComMA model



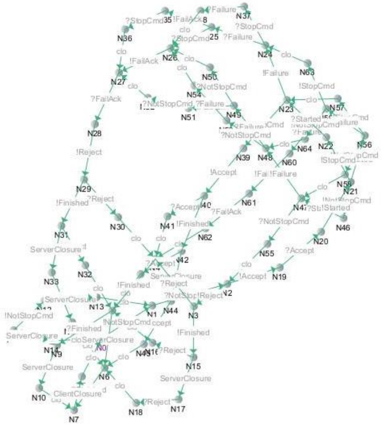
Petri net

Server ComMA model



Petri net

Connect nets and export to PNML file



Use open-source Petri net Analysis Tools (PnAT) to compute reachability graph and check for termination (does not consider data)

```
**************************************************
  Property Check for Weak Termination
**************************************************

> Checking for Boundedness..

[ Summary ]

<+> Weak Termination: OK
<+> The net is safe!
**************************************************
```

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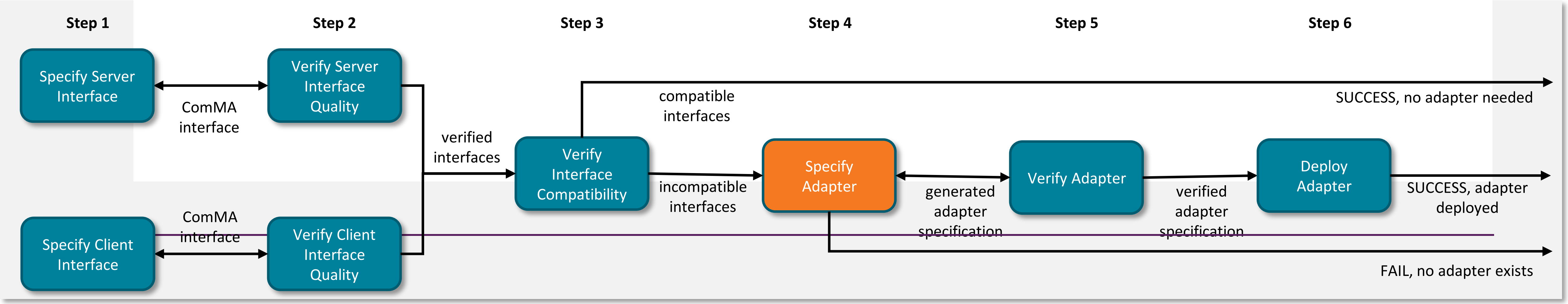


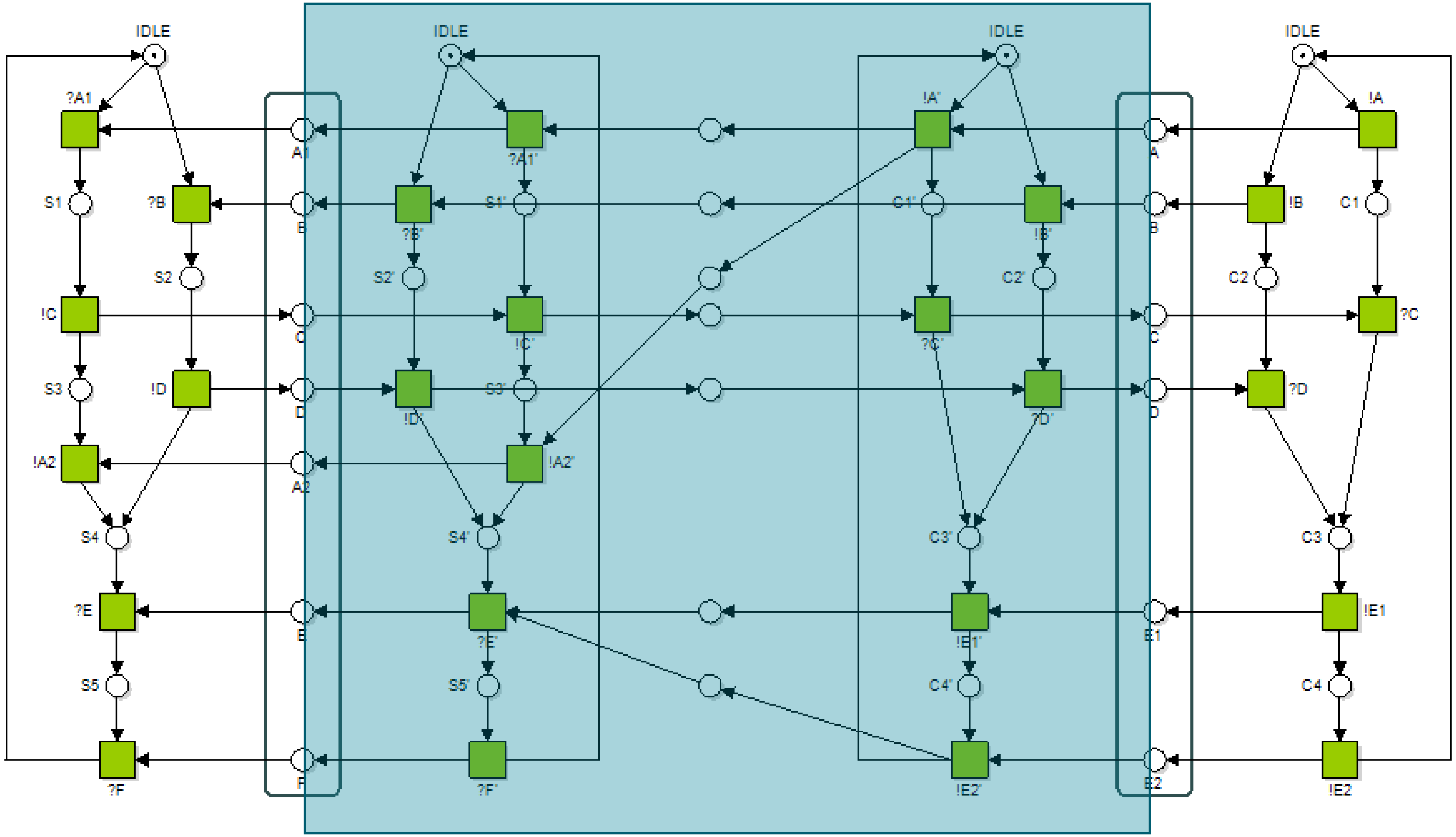
GENERATE ADAPTER

- Overview of adapter generation approach
  - **ComMA Mapping DSL** describes relation between messages for server and client
  - Adapter **encodes mapping rules** and is responsible for **transformations**
  - DSL generates **adapter Petri net specification**

Mapping Rules

cs.PTOn -> sr.PTOn;
cs.PTGetState -> sr.PTGetState;
cs.PTOff -> sr.PTOff, cr.PTState;
ss.PTState -> cr.PTState;

SERVER AND CLIENT CONNECTED THROUGH AN ADAPTER



Mapping Rules

cs.A -> sr.A1, sr.A2
cs.B -> sr.B
ss.C -> cr.C
ss.D -> cr.D
cs.E1, cs.E2 -> sr.E
-> sr.F

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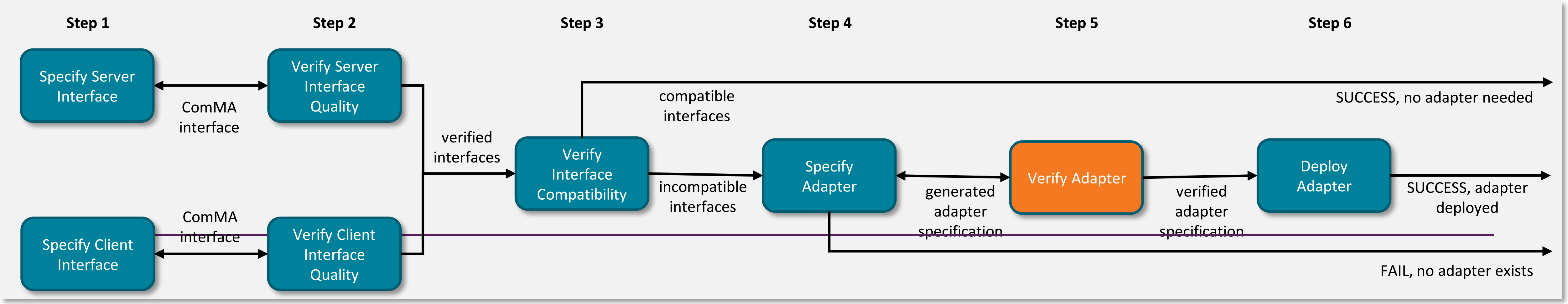

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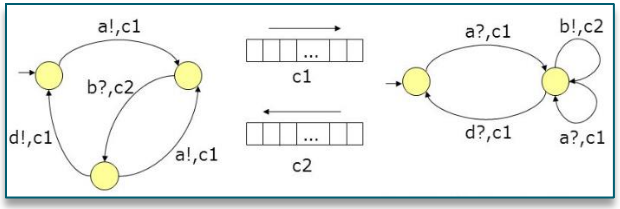

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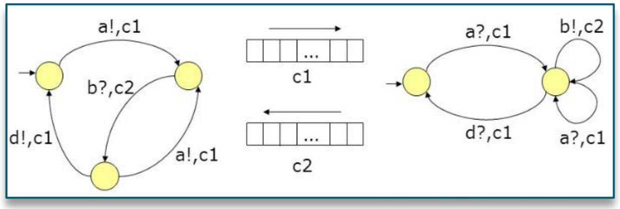
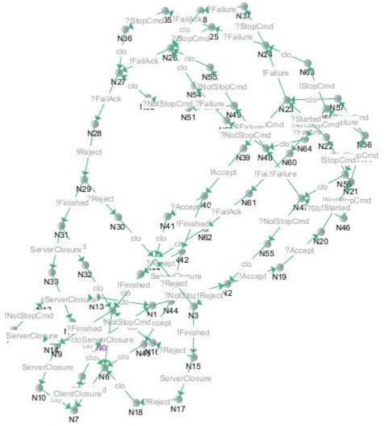


ComMA Mapping DSL

Petri net | **Petri net** | **Petri net**

Connect nets and export to PNML file



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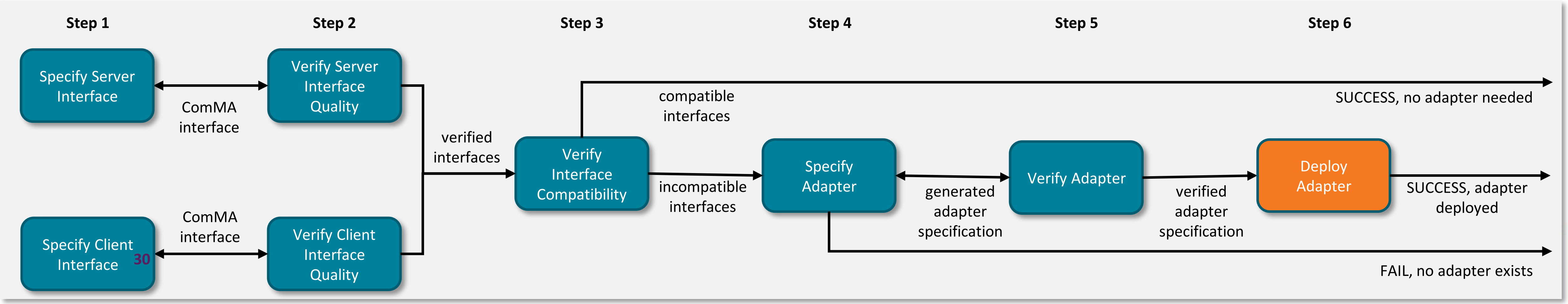


BIGGER BIGGER PICTURE WITH COMMA

Model Inference →

Structure

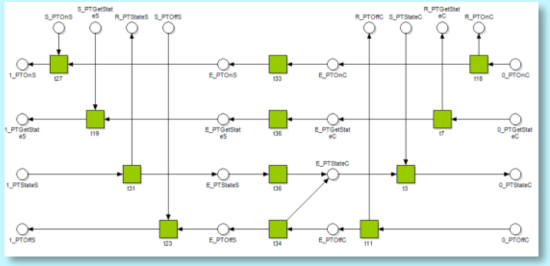
```
commands
    Status PowerOn
    void   PowerOff
    bool Zoom(in real factor,
              out real result,
              out real scale
    )
    Picture TakePhoto(Time t)
    int  GetPictureNumber
signals
    ProvideStatus
notifications
    CameraStatus(Status s)
    Click
}
```

Behavior

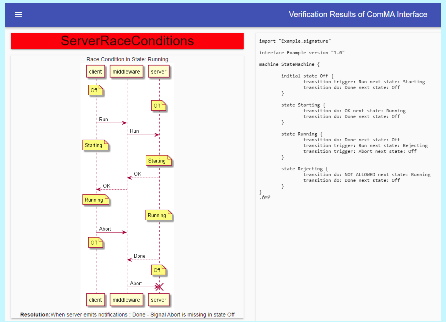
```
initial state Off {
    transition trigger: ICamera::PowerOn
        do: reply(Status::OnOK)            next state: SwitchingOn
        OR
        do: reply(Status::OnFailed)        next state: Off
}
state SwitchingOn {
    transition do: ICamera::CameraStatus(Status::OnOK)
                                                   next state: On

    transition do: ICamera::CameraStatus(Status::OnFailed)
                                                   next state: Off
}
```

Generated →

Adapter Generation



Model Quality Checks

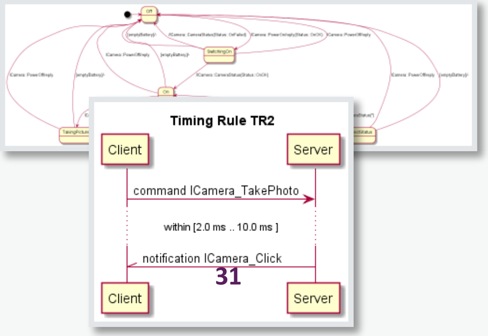


Code Stubs

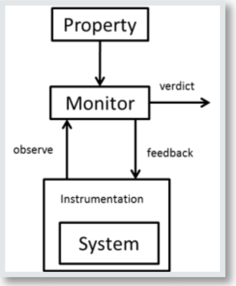
```
switch(state) {
  case ON {

  }
  case OFF{

  }
}
```

Generated ↓

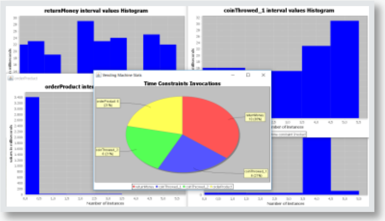
Visualization



Monitoring



Statistics



Simulation

Documentation

OPEN INNOVATION AT WORK!

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- This project is a text book example of **open innovation** at work
    - Initial prototype was based on theory and tools from previous European academic research
    - Leveraged Eclipse CommaSuite (ESI&Philips) and results **were contributed back to open source**
    - **Methodology** and **proof-of-concept tool** delivered to Thales to **evaluate for adoption**
    - **Three UvA students** contributed to the research, publishing **theses** and **academic papers**

- Developed knowledge transferred in a **two-day course**
    - Two versions of course, one based on **Petri nets** and one on **CommaSuite**
    - Course has been given to >300 participants at Thales and UvA

3

VARIABILITY AND EVOLUTION IN SOFTWARE PLATFORMS

2024-?

INTRODUCTION

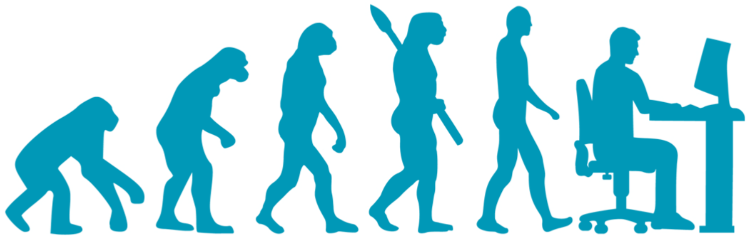
- There is a trend towards **increased customization** in many industries, including high-tech equipment
  - Every customer wants slightly different features
  - Puts pressure on **R&D effort**, **delivery times,** and **cost** of products

- Industry has been addressing this challenge by moving towards a **platform-based approach**
  - New **customized products** can be derived by configuring a general set of **building blocks**
  - Often requires a transition from project organizations to **product organizations**
  - From **engineering-to-order** to **configure-to-order**

LONG LIFE TIMES AND CONTINUOUS EVOLUTION

- High-tech equipment has long life times of **several decades** in the field
  - Need to cope with end of life of components, spare parts, and maintenance
  - The system **outlives** many of its constituent technologies, in particular digital technologies

- There is a need for the system to **continuously evolve** during its life time
  - System needs upgrades to **new (digital) technology and software** to remain operational
  - Customer wants **improved functionality** that increase the added value



PROBLEM STATEMENT

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- Evolving system variants requires substantial **re-development effort** and is **costly**
  - Essentially a new iteration through the complete development cycle
  - Product configurations must be **updated** to reflect new features
  - System is often **manually ported** to new software technologies
  - System must be **re-verified**, including its **performance**, which is an emerging property from interacting hardware and software components

- This project addresses the challenge of **reducing the time and cost** associated with **system evolution** at the level of the **software platform** (infrastructure)

VISION AND GOAL

Vision

A **product-based approach** with **building blocks** to quickly **configure custom solutions** for each customer that **always satisfy their (performance) requirements** throughout their **entire lifecycle**

Long-term goal

A **model-based methodology** and supporting tool that enables custom solutions to be **specified in a technology-agnostic manner**, and where a software deployment that **satisfies (performance) requirements** is **automatically generated** and regenerated, as software technologies evolve

RESEARCH QUESTIONS AND APPROACH FOR 2024

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1. To what extent can the generic configuration model be **decoupled** from the deployment technology?
    - Investigating a **domain-specific language** that describes system modules at the level of the capabilities the provide and require, and the hardware and software components they need to realize functionality
    - Specification is **independent** from the software technology used, e.g. for containerization or orchestration, such as Kubernetes or Docker
    - Automatic generation of deployments for different technologies addresses evolution of the **level of the platform**, reducing effort for all variants

2. How can we efficiently **identify a software deployment** that satisfy performance requirements for a particular product configuration and deployment technology?
    - Investigating a **learning-based approach** to optimize deployments for a **particular variant**
    - Performance verification successful if a (set of) deployment can be found that satisfies requirements for relevant loads

4

CONCLUSIONS

CONCLUSIONS

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- The system complexity of high-tech equipment is increasing
  - Market demands for **more functionality**, **customization**, and **evolvability**
  - ESI and its partners addresses this complexity challenge using **model-based systems engineering methodologies** in an **open innovation ecosystem**

- **Two industrial cases** related to variability and evolution of software in high-tech equipment were presented
  1. A model-based methodology for specification, verification, and adaptation of software interfaces based on domain-specific languages and Petri nets was presented and its impact discussed
  2. Problem description and research directions for a challenge to reduce the cost and effort related to variability and evolution at the level of the software platform

- We are happy to discuss this research with you and hear your **feedback** and **input**
  - … and let us know if you are interested in making the **next step** in your career ☺

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