# Dependability assurance of autonomous systems: an integrated formal approach

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# Dependability

- Dependability is a property of the system to deliver its services in a trustworthy way

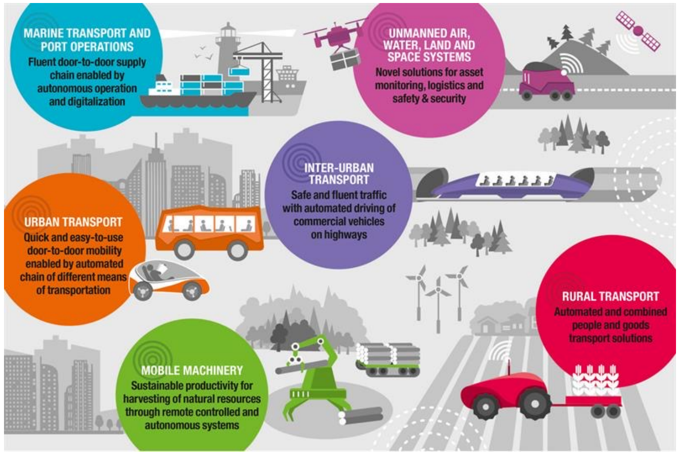
- It encompasses a wide set of requirements:
  - safety, reliability, security etc.

- Traditional dependability engineering: the goal is to demonstrate that the design is safe (reliable, secure etc.) under the given (constrained) environment model

# Autonomous systems

- An autonomous system is capable of delivering its services in a highly independent way.

- A fully autonomous system can
    - Gain information about the environment
    - Work for an extended period without human intervention
    - Move either all or part of itself throughout its operating environment without human assistance



**MARINE TRANSPORT AND PORT OPERATIONS**
Fluent door-to-door supply chain enabled by autonomous operation and digitalization

**UNMANNED AIR, WATER, LAND AND SPACE SYSTEMS**
Novel solutions for asset monitoring, logistics and safety & security

**INTER-URBAN TRANSPORT**
Safe and fluent traffic with automated driving of commercial vehicles on highways

**URBAN TRANSPORT**
Quick and easy-to-use door-to-door mobility enabled by automated chain of different means of transportation

**RURAL TRANSPORT**
Automated and combined people and goods transport solutions

**MOBILE MACHINERY**
Sustainable productivity for harvesting of natural resources through remote controlled and autonomous systems

- Essentially, it is an autonomous mobile agent with a high degree of self-awareness and self-management (and hence, non-determinism)

*But it is also a safety-critical system!*

# Formal methods in high-assurance system engineering

- Formal methods are mathematically rigorous techniques for the specification, development, and verification of SW and HW systems
  - Mathematical analysis is typically required for good system design

- Formal methods come in different flavors:
  - *Lightweight FM* – a formal specification precedes the actual design

  - *Correct-by-construction development frameworks*: refinement-based development (e.g., Event-B) and formal verification

  - *Theorem proving*: domain is formalized as a theory and verified by the machine-checked proofs

# Formal modelling and verification in Event-B

- Event-B is a formal state-based modelling framework based on set theory and first order logic
- System state is defined by a collection of variables (can be functions, relations etc)
- The dynamic system behaviour is described in terms of guarded commands (events):

  ***WHEN*** *predicate* ***THEN*** *assignment*

  *stimulus -> response*
- Events define state transitions (can also be non-deterministic)
- Model invariant defines a set of allowed (safe) states
  - Each event should preserve the invariant

***Machine*** *SimpleRobot*
***Variables*** *xposition*
***Invariant***
$xposition \in NAT \wedge$
$L\_Edge \leq xposition \leq R\_Edge$
***Initialisaton*** $xposition := 0$
***Events***
***StepLeft*** $\overset{def}{=}$
*WHEN* $xpositon \geq L\_Edge+1$
*THEN* $xposition := xposition-1$

***StepRight*** $\overset{def}{=}$
*WHEN* $xpositon \leq R\_Edge-1$
*THEN* $xposition := xposition+1$

***StepAnywhere*** $\overset{def}{=}$
*WHEN* $L\_Edge < xposition < R\_Edge$
*THEN*
$xposition :\in [xposition-1, xposition+1]$

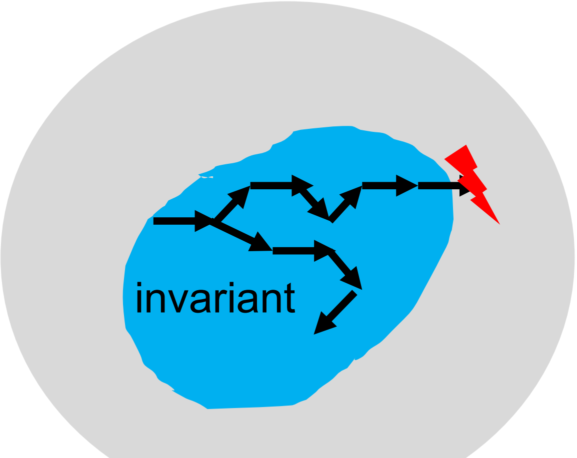
# Formal modelling and verification in Event-B: Rodin platform

- Rodin platform: Eclipse-based integrated modelling environment

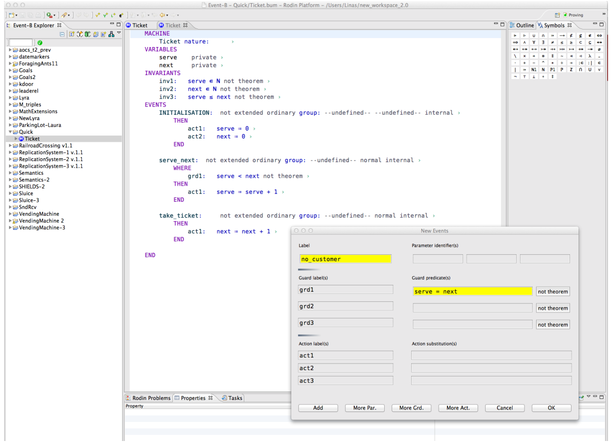
- Automates refinement process
  - Supports strong interplay between modelling and verification;
  - Reactive: analysis tools are automatically invoked in the background whenever a change in a model is made

- The platform is extendable by plug-ins extending the Event-B language and verification techniques
- Automated support for strongest evidence of safety – safety invariant
- Support for model checking

- High degree of automation of verification efforts



State space defined by types



```
MACHINE
    Ticket nature:      ›
VARIABLES
    serve    private ›
    next     private ›
INVARIANTS
    inv1:   serve ∈ ℕ not theorem ›
    inv2:   next ∈ ℕ not theorem ›
    inv3:   serve ≤ next not theorem ›
EVENTS
    INITIALISATION:  not extended ordinary group: --undefined-- --undefined-- internal ›
        THEN
            act1:   serve ≔ 0 ›
            act2:   next ≔ 0 ›
        END

    serve_next:  not extended ordinary group: --undefined-- normal internal ›
        WHERE
            grd1:   serve < next not theorem ›
        THEN
            act1:   serve ≔ serve + 1 ›
        END

    take_ticket:    not extended ordinary group: --undefined-- normal internal ›
        THEN
            act1:   next ≔ next + 1 ›
        END

END
```

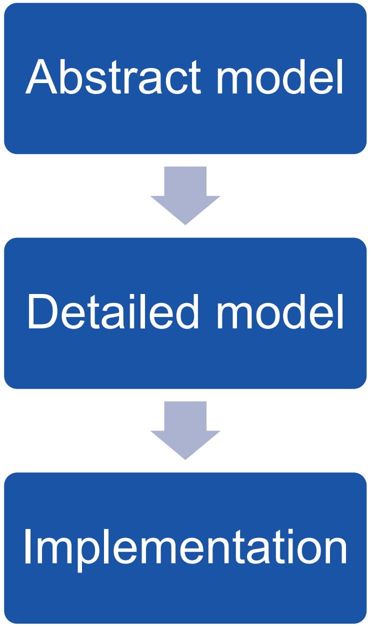
Label: no_customer

| Guard label(s) | Guard predicate(s) | |
|---|---|---|
| grd1 | serve = next | not theorem |
| grd2 | | not theorem |
| grd3 | | not theorem |

| Action label(s) | Action substitution(s) |
|---|---|
| act1 | |
| act2 | |
| act3 | |

Add | More Par. | More Grd. | More Act. | Cancel | OK

# Correct-by-construction development: refinement



Abstract model

Detailed model

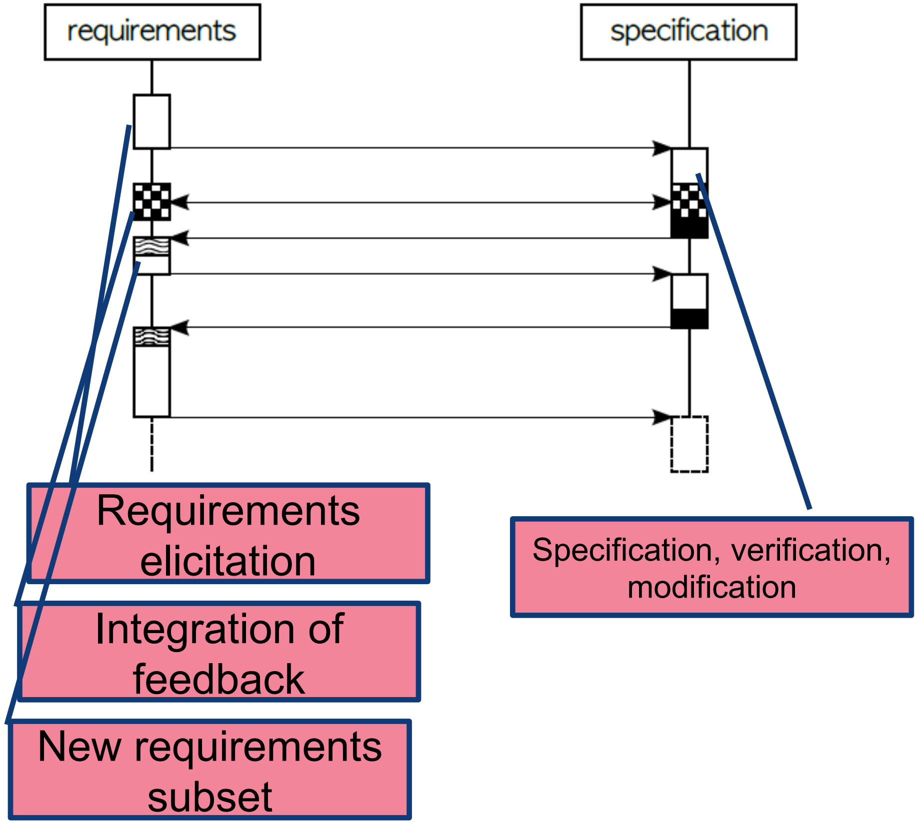
Implementation

- Abstract specification: defines essential behavior and invariant properties of system
- Refinement transform specification to add new behavior, reduce non-determinism
- The properties of the abstract specification are preserved throughout the entire refinement chain

- For example, we can add a variable *yposition* to our *SimpleRobot* specification and define movement along y axis.
  - Requires to prove that initial invariant is maintained, i.e., we refined implicit *skip* statements – superposition refinement
- We might also decide to replace rectangular coordinates with polar – data refinement
- We need to define the invariant connecting new and old state space $r \times \cos(\theta) \wedge y = r \times \sin(\theta)$ and prove that it is always preserved

# Iterative model-based development in Event-B

- Each iteration
  - aims at defining and formalising a certain subset of system requirements
  - incorporating a feedback provided by the formalisation into the requirements definition.
- Refinement step: introduction of new variables and events
- Proofs verify that refined model adheres to the abstract model



Requirements elicitation

Integration of feedback

New requirements subset

Specification, verification, modification

# Systems engineering and software verification: systems approach

A system requirement *SysReq* is a relation between a set *M* of monitored variables and a corresponding set *C* of controlled variables:

$$SysReq \subseteq M \times C$$

A software requirement *SofReq* is a relation between a set *I* of input variables and a corresponding set *0* of output variables:

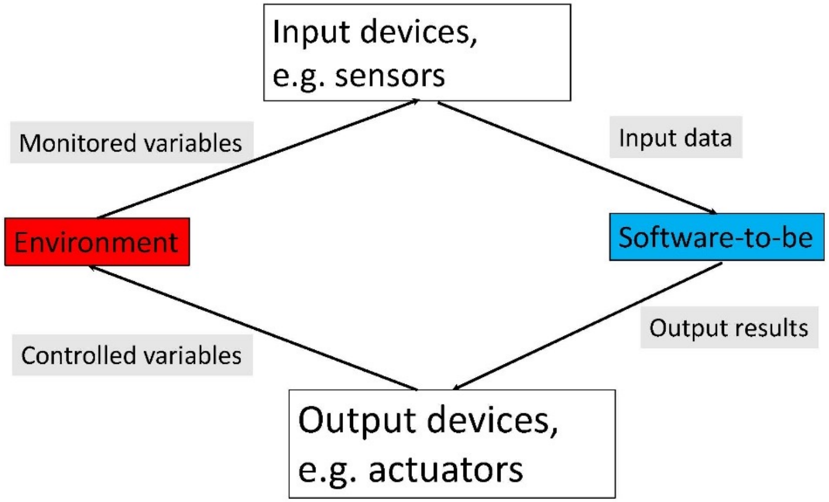
$$SOFREQ \subseteq I \times O$$

we need to provide *satisfaction arguments* in the form:

*{SOFREQ,ASM, DOM}* I= *SysReq*

*DOM* Domain properties

*ASM* Assumptions



Parnas and Madley (1995) Four-variable model

# Formal modelling of safety-critical systems

- Formal modelling: avoid design faults
- Fault tolerance: hardware random faults, residual faults are unavoidable,
  - Need to guarantee deterministic behavior in different failure modes

- Modelling failure occurrence and refining according to different failure modes allows us to derive properties preserved under different failure conditions

- Augmenting model with probabilistic data (failure rate) we enable quantitative verification
  - For example, express properties like probability of catastrophic failure within n time units

# Achieving Dependable Autonomy

- New challenges:
  - Open and complex operating environment
  - Continuous evolution (e.g., based on learning)
  - Inherent uncertainty – internal (complex failure modes, component interaction) and external (complex operating environment)

- Trustworthy system functioning becomes dependant on new complex factors:
  - Networks: is QoS sufficient for hard real-time safety-critical functions?
  - Security: can data for making safety-critical decisions be trusted ?
  - Resources: are the components involved into implementing safety-critical functions have sufficient power level?

- *Building an exhaustive model of the environment at design time is unfeasible and hence run-time verification is important*
- *Safety depends on many factors, hence multi-aspect models are required*

# Different degrees of uncertainty

- Unforeseen types of hazards
  - We do not know what we do not know, e.g., unforeseen scenarios or feature interactions
- Foreseen types of hazards
  - We do not know for sure, e.g., operational environment, coverage of different situations
- Known hazards
  - Sufficient observability and controllability

# Strategic, tactic and active safety

- Strategic: plan ahead to maximise safety
  - Safety-aware mission planning
- Tactic: monitor and re-plan at run-time
  - Run-time system and environment monitoring and planning
- Active (or emergency): mitigate and remove hazard occurrence
  - Akin human reflexes: hazard detection and default “safety escape”

# Modelling and design challenging

- We need to combine design and run-time efforts to monitor safety and resource efficiency and adapt to operating conditions at run-time

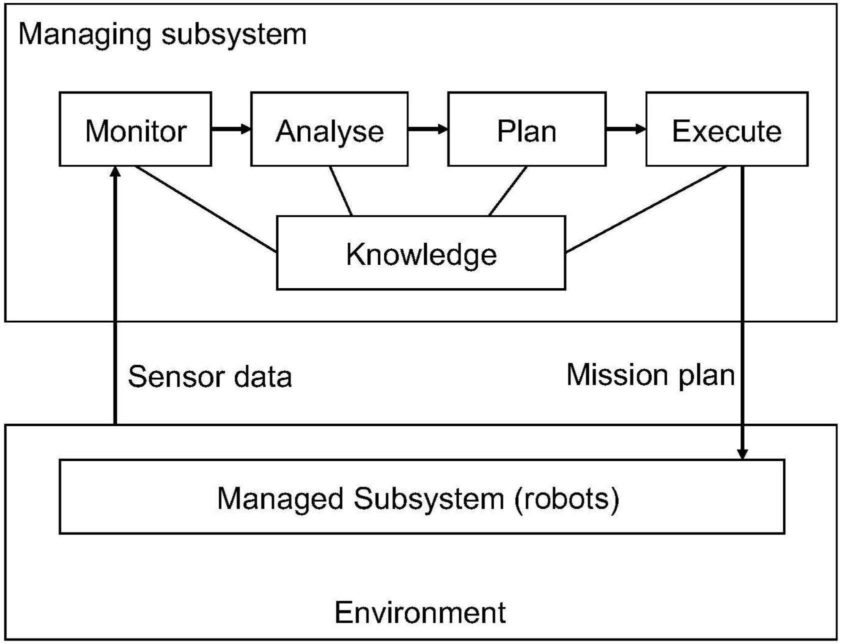
- Need for multi-layered dependability management that combines design and run-time safety mechanisms
  - Complex, tangled and hence, requires formal modelling

- Formal modelling
  - Modelling and verification of layered architecture enabling run-time adaptation
  - Specification and verification of safety conditions
  - Design and verification of a safety net to cope with unforeseen hazards and around AI components

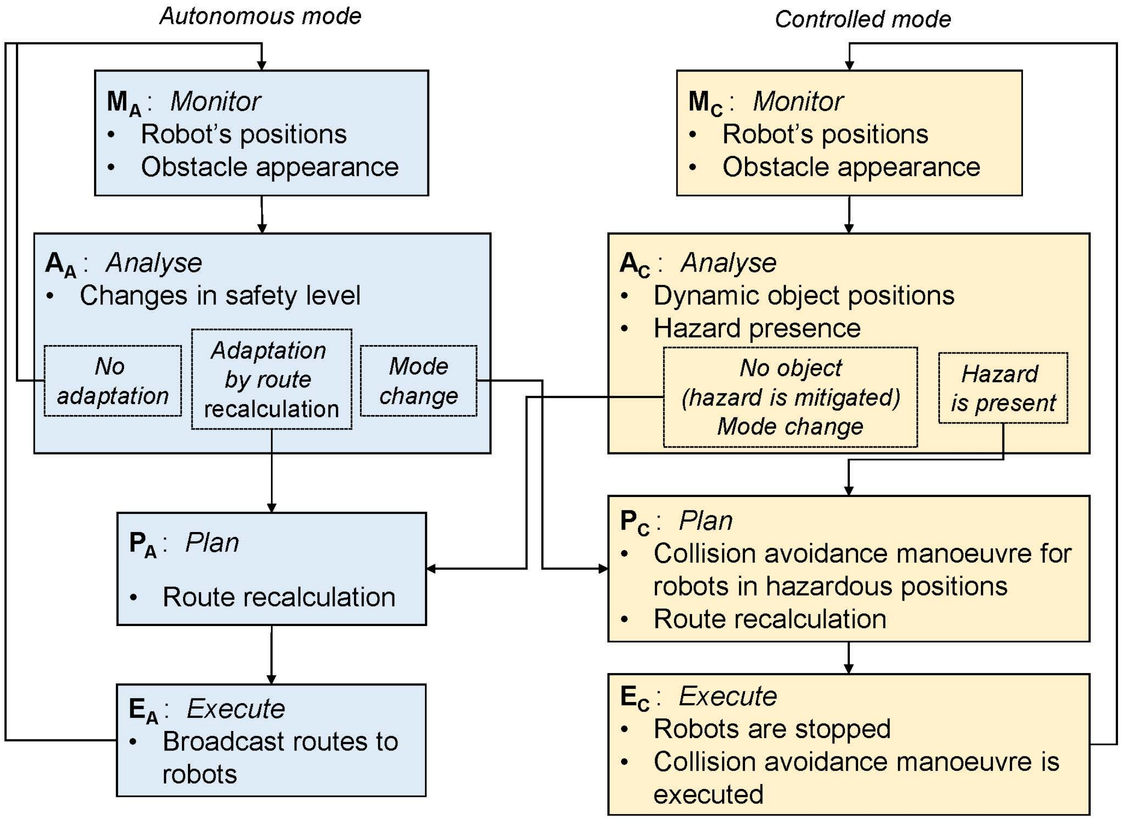
- Run-time planning algorithms:
  - Design high performance planning algorithms capable of controlling autonomous agents at run-time in safe and efficient way

# Self-adaptive architecture

- We adopt MAPE-K architectural pattern:
  - Cyclic behaviour
  - At each cycle: M-Monitor, A-Analyse, P-Plan, E- Execute over shared K-Knowledge



# Adaptive architecture of multi-agent control: system level



*Autonomous mode*

**M$_A$**: *Monitor*
- Robot's positions
- Obstacle appearance

**A$_A$**: *Analyse*
- Changes in safety level

*No adaptation*

*Adaptation by route recalculation*

*Mode change*

**P$_A$**: *Plan*
- Route recalculation

**E$_A$**: *Execute*
- Broadcast routes to robots

*Controlled mode*

**M$_C$**: *Monitor*
- Robot's positions
- Obstacle appearance

**A$_C$**: *Analyse*
- Dynamic object positions
- Hazard presence

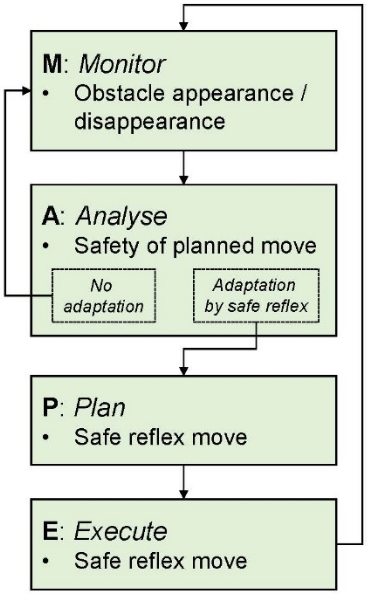
*No object (hazard is mitigated) Mode change*

*Hazard is present*

**P$_C$**: *Plan*
- Collision avoidance manoeuvre for robots in hazardous positions
- Route recalculation

**E$_C$**: *Execute*
- Robots are stopped
- Collision avoidance manoeuvre is executed

# Adaptive architecture of fleet control: agent's level



- At agent's level MAPE-K architectural pattern is used to implement "emergency response" – confine damage or mitigate hazard impact
- Safety reflex mechanism is designed to cope with unexpected hostile changes in the environment or mistakes in AI-based planning
- Safety properties are distributed through different architectural layers and have intricate interdependencies

# Modelling and verifying multi-agent control architecture

A chain of model refinement:

- Abstract specification: abstract representation of a progress of a mission execution;
- 1st refinement: abstract model of system-level MAPE-K cycle;
- 2nd refinement: introducing abstract behaviour of agents; conditions triggering re-calculating planning and adaptation logic;
- 3rd refinement: introducing model of dynamically emerging hazards and change of modes
- 4th refinement: modelling agent’s MAPE-K loop
- Result: formally verified safety requirement (in out case it was collision avoidance)

# Developing planning algorithm

- Formal modelling allowed us to demonstrate safety of proposed architectural solution
- We also modelled unreliable communication and hand-over from failed to functioning agent
- However, we need an algorithm capable of generating route planning for the fleet in run-time
- The main requirement to the algorithm:
    - High performance
    - Minimising resource consumption
    - Maximasing safety
- Optimisation problem: solved using AI

# Work in progress and challenges ahead (1/2)

- Autonomous systems are connected systems. Hence security is in the picture
  - We are working on formal modelling of safety-security interactions
    - Which safety properties are violated under different attacks?
  - Open challenge: safety in presence of untrusted agents – deriving architectures and protocols

- Deriving run-time safety monitors from system model
  - Monitoring against unknown hazards
  - Safety monitoring in presence of evolution (due to learning)
  - Change-sensitive model verification

- Conditional safety modelling based on QoS
  - Can we define a two-way approach: can safety-critical application reconfigure network to achieve the required QoS?
  - Quantitative rely-guarantee approach
  - Resource negotiations and coordination

# Work in progress and challenges ahead (2/2)

- Multi-aspect modelling
  - Resource-explicit modelling
  - Projection of system-level model into different types of models: verification of timing, resources, quantitative dependability guarantees
  - Flexible adaptive architectures

- Integration with simulation platforms
  - Modelling and verifying safety of behaviour trees
  - Verification of different robotic library components

- Fundamental challenge: support for compositionality and defining different abstractions layers

# Thank you!