ASML Embedded Systems Innovation BY TNO STW Enabling new technology RobustCPS

Compositional Specification of Functionality and Timing of Manufacturing Systems

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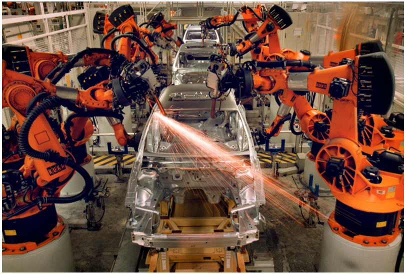
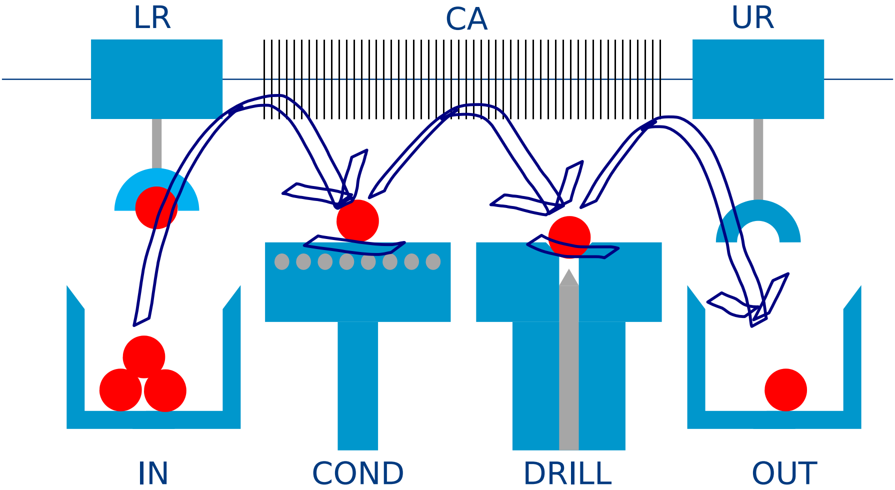
Manufacturing Systems



Goal:

- Formal modeling approach for manufacturing systems with Compositional Specification of Functionality and Timing.

Example Manufacturing System



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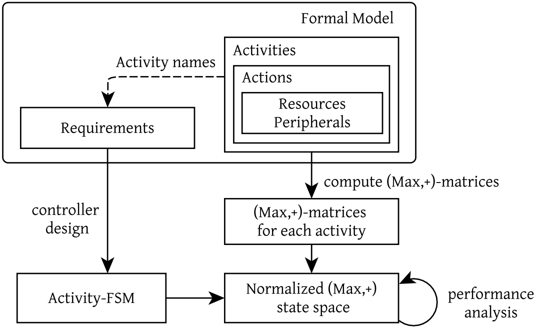
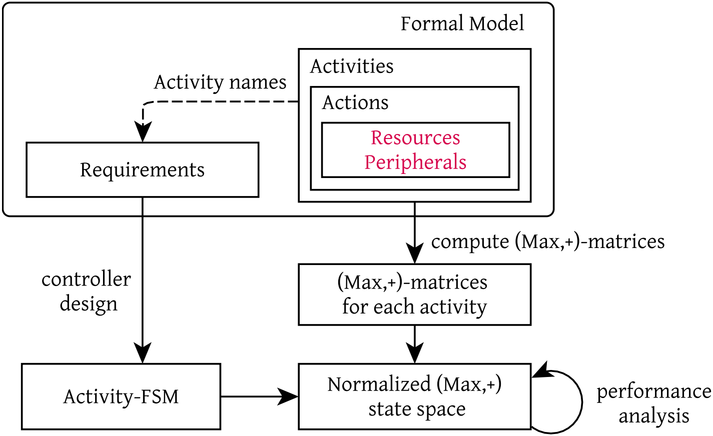
Formal Modeling Approach

Modeling and Analysis to find a throughput-optimal safe controller for nominal behavior.



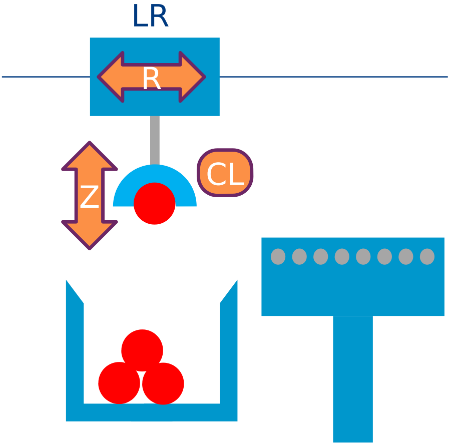
Formal Model: Resources and Peripherals



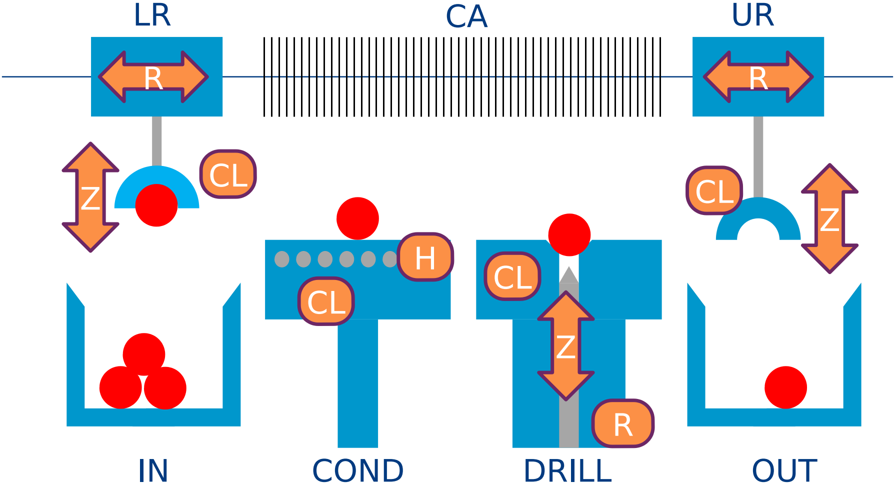
Formal Model: Resources and Peripherals

- Set of peripherals that can execute a number of actions.
- Peripherals are aggregated into resources.

- Resource Load Robot LR has peripherals motor R, motor Z, clamp CL.



Formal Model: Resources and Peripherals



Formal Model: System behavior

Resources and peripherals: model the system **components.**

System **behavior** is modeled on three levels:

1. Actions executed by peripherals.

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2. Activities to describe scenarios of end-to-end **deterministic behavior.**

   An activity consists of a set of actions and dependencies among these actions.

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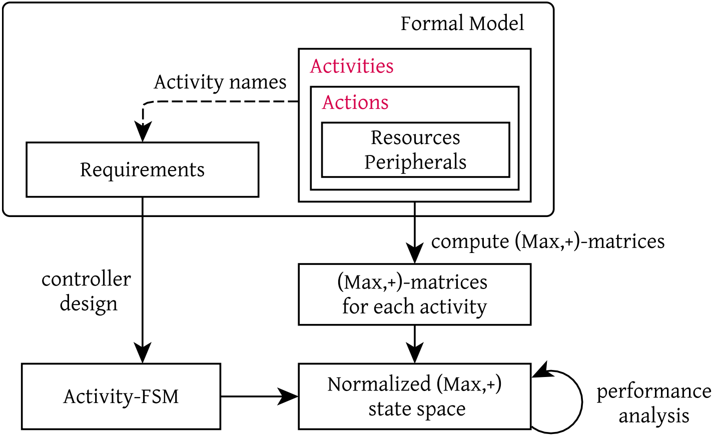
   An activity consists of a set of actions and dependencies among these actions.
3. Activity sequences describe **orderings of activities.**

Formal Model: Activities and Actions



Formal Model: Activities and Actions

Activities in the Twilight system:

Operations on a product:

- Condition
- Drill

Moving a product:

- LR_PickFromInput
- LR_PickFromCond
- LR_PickFromDrill
- LR_PutOnCond
- LR_PutOnDrill
- UR_PickFromCond
- UR_PickFromDrill
- UR_PutOnCond
- UR_PutOnDrill
- UR_PutOnOutput

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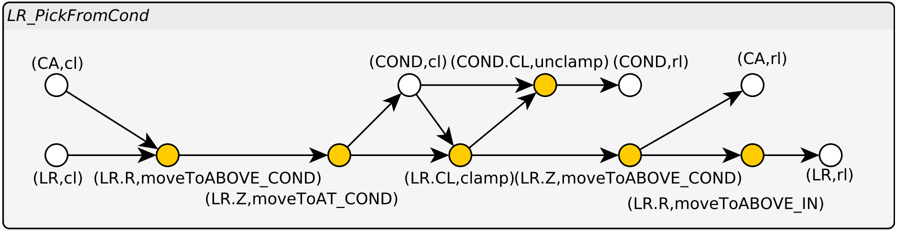
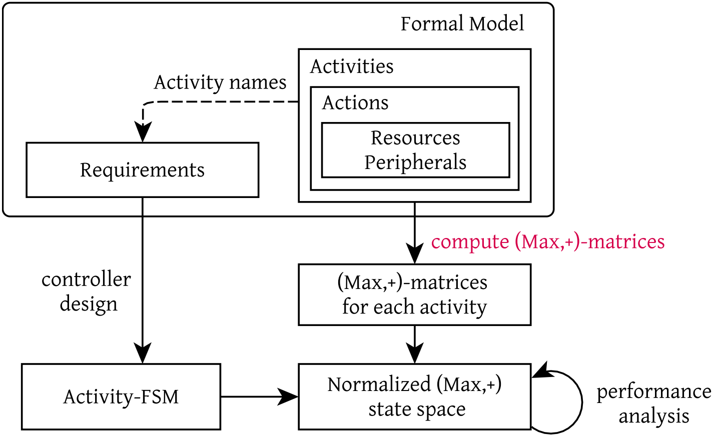
Formal Model: Activities and Actions

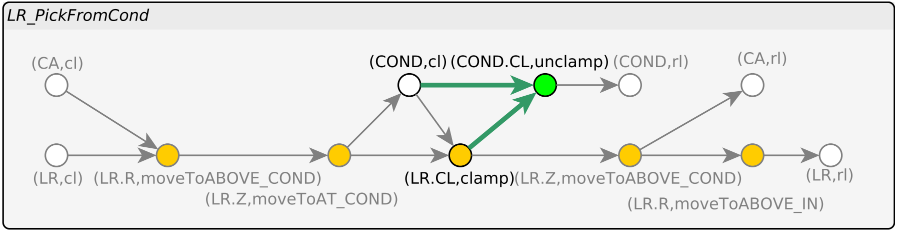


- Function of activity:
  Move LR to COND, pick up the ball, move back to home position
- Actions: cl claim, rl release, unclamp, clamp, moves
- Involved resources:
  Collision Area (CA), Load Robot (LR), Conditioner (COND)

Formal Model: Timing



Formal Model: Timing



Two essential characteristics in activity execution:

1. synchronization: waits for incoming dependencies to finish

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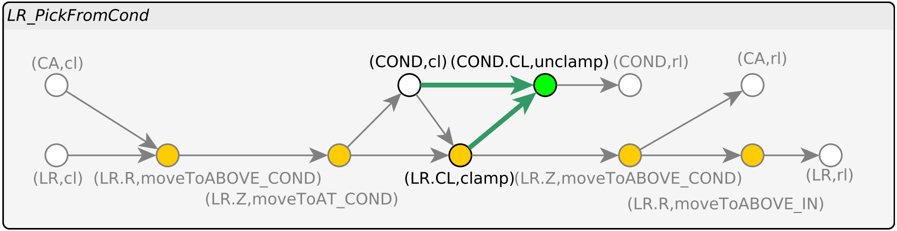
Formal Model: Timing



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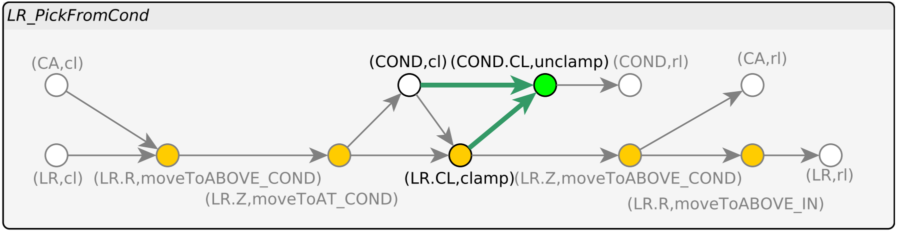

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These characteristics correspond well to the (max,+) operators max and addition in (max,+) algebra.

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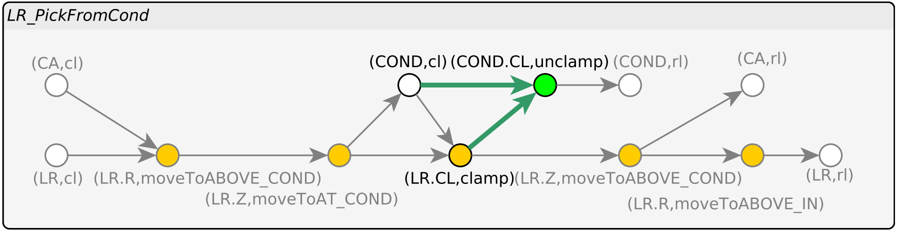

Two essential characteristics in activity execution:

1. synchronization: waits for incoming dependencies to finish
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We use this algebra to capture the timing behavior of the activity in a (max,+) matrix.

Formal Model: Timing

- (max,+) matrix: $M_{LR\_PickFromCond} = \begin{bmatrix} .. & .. & .. \\ .. & .. & .. \\ .. & .. & .. \end{bmatrix}$

Formal Model: Timing

- (max,+) matrix: $M_{LR\_PickFromCond} = \begin{bmatrix} .. & .. & .. \\ .. & .. & .. \\ .. & .. & .. \end{bmatrix}$
- resource availability vector: $\gamma_{begin} = \begin{bmatrix} \gamma_{begin}(\mathsf{CA}) \\ \gamma_{begin}(\mathsf{LR}) \\ \gamma_{begin}(\mathsf{COND}) \end{bmatrix}$

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Formal Model: Timing

- (max,+) matrix: $M_{LR\_PickFromCond} = \begin{bmatrix} .. & .. & .. \\ .. & .. & .. \\ .. & .. & .. \end{bmatrix}$
- resource availability vector: $\gamma_{begin} = \begin{bmatrix} \gamma_{begin}(\mathsf{CA}) \\ \gamma_{begin}(\mathsf{LR}) \\ \gamma_{begin}(\mathsf{COND}) \end{bmatrix}$
- New vector γ_{end} by matrix multiplication in (max,+) algebra:

$$\underbrace{\begin{bmatrix} \gamma_{end}(\mathsf{CA}) \\ \gamma_{end}(\mathsf{LR}) \\ \gamma_{end}(\mathsf{COND}) \end{bmatrix}}_{\gamma_{end}} = \underbrace{\begin{bmatrix} .. & .. & .. \\ .. & .. & .. \\ .. & .. & .. \end{bmatrix}}_{M_{LR\_PickFromCond}} \otimes \underbrace{\begin{bmatrix} \gamma_{begin}(\mathsf{CA}) \\ \gamma_{begin}(\mathsf{LR}) \\ \gamma_{begin}(\mathsf{COND}) \end{bmatrix}}_{\gamma_{begin}}$$

Formal Model: Timing

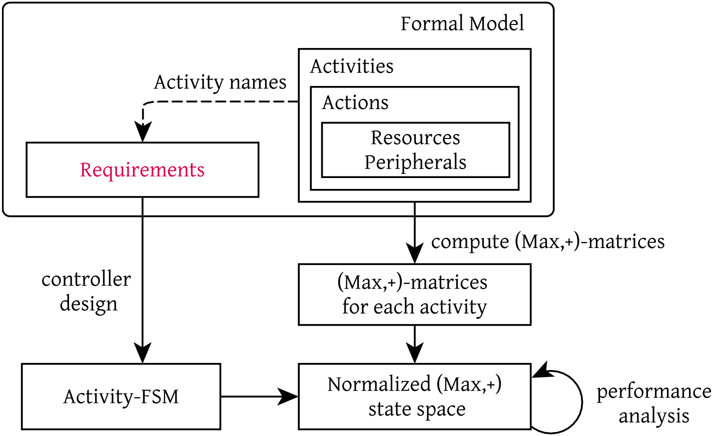
Now consider an activity sequence, for instance:

$$\text{Condition} \; ; \; \text{LR\_PickFromCond}.$$

Then, given begin system state γ_{begin},
the end system state γ_{end} is given by:

$$\gamma_{end} = M_{\text{LR\_PickFromCond}} \otimes M_{\text{Condition}} \otimes \gamma_{begin}.$$

Formal Model: Requirements



Formal Model: Requirements

What we have so far:

- Activities: specify scenarios of **deterministic behavior.**
- Activity sequences: to describe **orderings of activities.**

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- Activities: specify scenarios of **deterministic behavior.**
- Activity sequences: to describe **orderings of activities.**

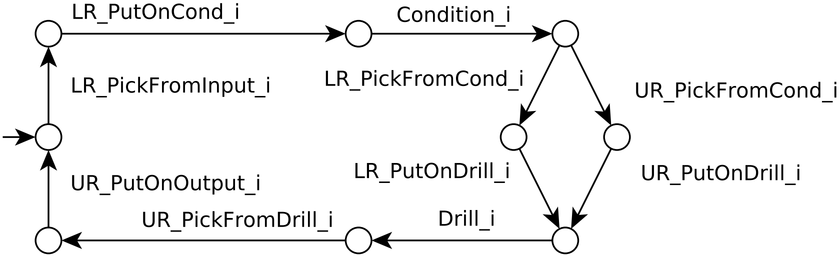
Not all orderings are however valid. We need requirements on allowed orderings to enforce:

- No product collisions at product locations.
- No collisions of robots.
- Life cycle of products.

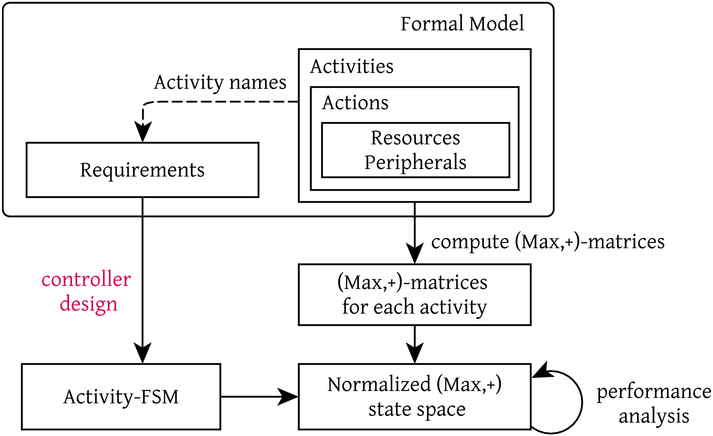
Formal Model: Requirements

Life cycle automaton: each product follows the same life cycle.

- We restrict to forward moves only.
- Scheduling freedom between LR and UR.



Controller Design



Controller Design

Formal Model specifies:

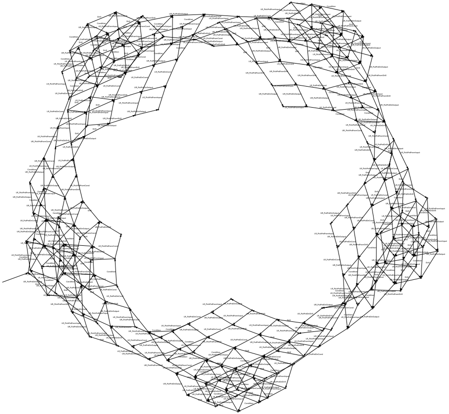
- Activities in system.
- Requirements on allowed activity orderings.

Controller Design:

- Design a controller that respects the requirements.
- For our example, we use supervisory controller synthesis to obtain an Activity-FSM of all allowed activity sequences.
- Activity-FSM is guaranteed to be deadlock-free and functionally correct with respect to the requirements.
- In this step we can **abstract from the timing !**

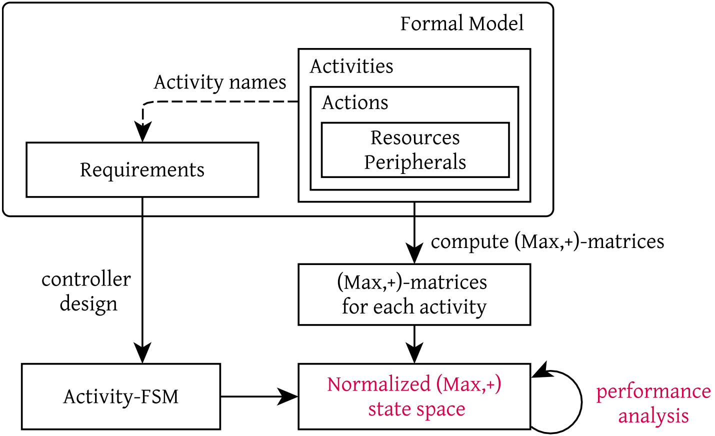
Controller Design

Activity-FSM after synthesis (245 locations, 510 transitions):



Models all allowed activity sequences.

Performance Analysis



Performance Analysis

What we have achieved so far:

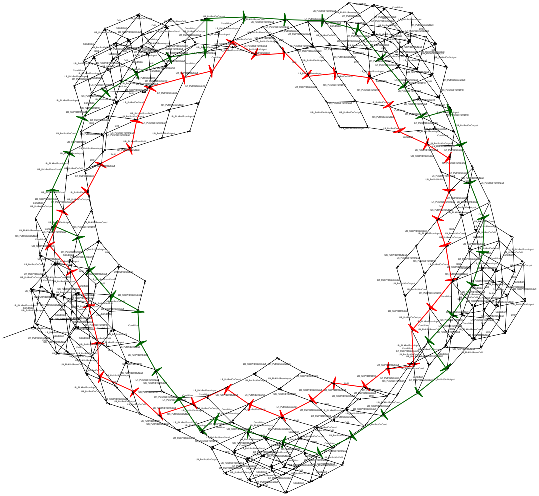
- Activity-FSM that models all allowed activity sequences.
- Timing matrix for each activity.

Now:

- Combine the (max,+) timing matrices and Activity-FSM.
- Explore normalized (max,+) state space, which is finite.
- Find optimal controller by performance analysis on traces in the state space.

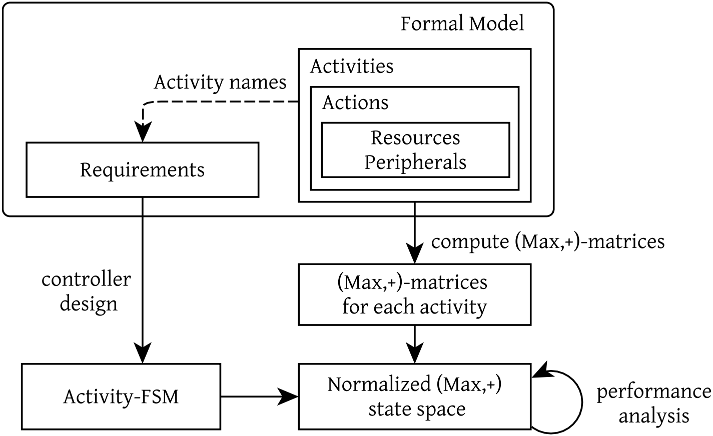
Performance Analysis on Twilight System

Using performance analysis algorithm to find guaranteed throughput and optimal controller.



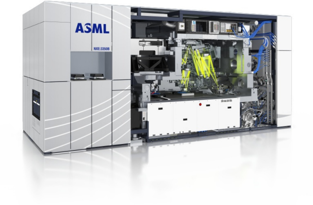
Recap: Formal Modeling Approach

Compositional Specification of Functionality and Timing.



Industrial use case: ASML

- Semantic underpinning of wafer handling specification tool.
- Model resources, peripherals, actions, activities.
- But also: motion paths of robots, symbolic positions.
- Calculate timing of move actions from the specification.
- Current research: specification of wafer logistics for nominal behavior.



ASML

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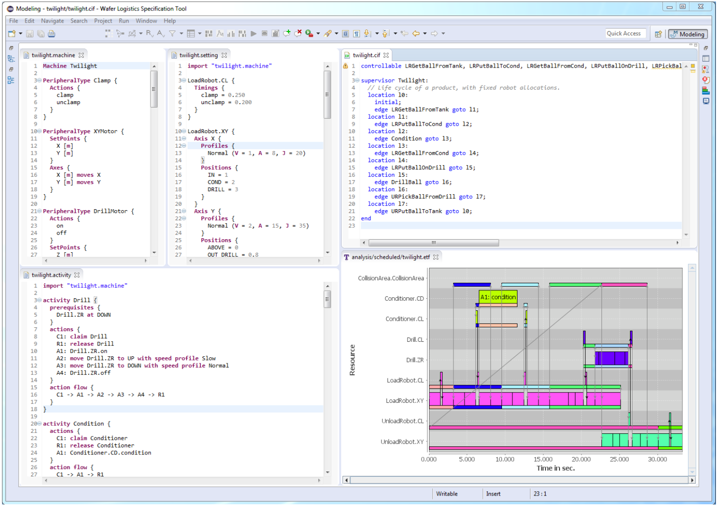

twilight.machine

```
Machine Twilight

PeripheralType Clamp {
  Actions {
    clamp
    unclamp
  }
}

PeripheralType XYMotor {
  SetPoints {
    X [m]
    Y [m]
  }
  Axes {
    X [m] moves X
    Y [m] moves Y
  }
}

PeripheralType DrillMotor {
  Actions {
    on
    off
  }
  SetPoints {
    Z [m]
```

twilight.setting

```
import "twilight.machine"

LoadRobot.CL {
  Timings {
    clamp = 0.250
    unclamp = 0.200
  }
}

LoadRobot.XY {
  Axis X {
    Profiles {
      Normal (V = 1, A = 8, J = 20)
    }
    Positions {
      IN = 1
      COND = 2
      DRILL = 3
    }
  }
  Axis Y {
    Profiles {
      Normal (V = 2, A = 15, J = 35)
    }
    Positions {
      ABOVE = 0
      OUT DRILL = 0.8
```

twilight.cif

```
controllable LRGetBallFromTank, LRPutBallToCond, LRGetBallFromCond, LRPutBallOnDrill, LRPickBal

supervisor Twilight:
  // Life cycle of a product, with fixed robot allocations.
  location l0:
    initial;
    edge LRGetBallFromTank goto l1;
  location l1:
    edge LRPutBallToCond goto l2;
  location l2:
    edge Condition goto l3;
  location l3:
    edge LRGetBallFromCond goto l4;
  location l4:
    edge LRPutBallOnDrill goto l5;
  location l5:
    edge DrillBall goto l6;
  location l6:
    edge URPickBallFromDrill goto l7;
  location l7:
    edge URPutBallToTank goto l0;
end
```

twilight.activity

```
import "twilight.machine"

activity Drill {
  prerequisites {
    Drill.ZR at DOWN
  }
  actions {
    C1: claim Drill
    R1: release Drill
    A1: Drill.ZR.on
    A2: move Drill.ZR to UP with speed profile Slow
    A3: move Drill.ZR to DOWN with speed profile Normal
    A4: Drill.ZR.off
  }
  action flow {
    C1 -> A1 -> A2 -> A3 -> A4 -> R1
  }
}

activity Condition {
  actions {
    C1: claim Conditioner
    R1: release Conditioner
    A1: Conditioner.CD.condition
  }
  action flow {
    C1 -> A1 -> R1
```

Future work

Research directions:

- Size of state space: modular synthesis techniques.
- More intuitive requirement modeling using state-based expressions.
- Uncontrollable behavior: extend formalism, new throughput analysis and optimization techniques.

Conclusions: Formal Modeling Approach

- Compositional Specification of Functionality and Timing.
- Functionality:
  - Describe deterministic behavior using **activities.**
  - Controller choices determine the **order of these activities.**
  - Separation between deterministic behavior and nondeterministic behavior.
  - Controller design on activity level, **abstraction from timing.**
- Timing:
  - Fixed timing for actions.
  - Timing behavior of activities captured in **matrices.**
  - System behavior: **max-plus state space**, timing analysis.

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