Twinning-by-Construction:

Ensuring Correctness for Self-Adaptive Digital Twins

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26.10.2022, ISoLA 2022

Digital Twins and Twinning

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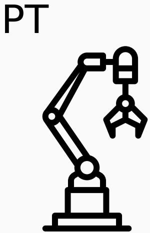

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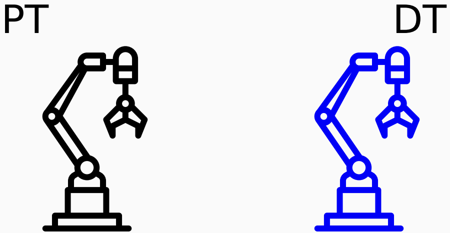

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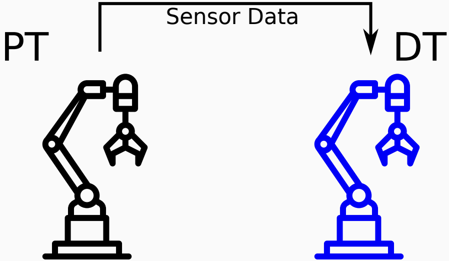

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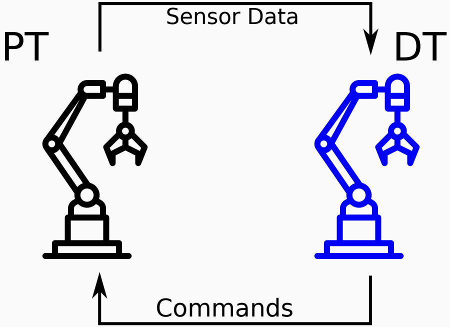

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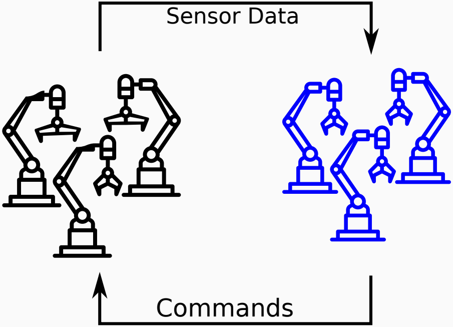

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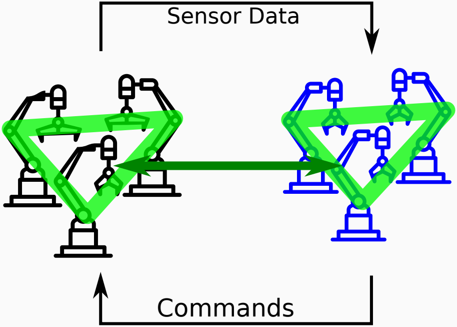

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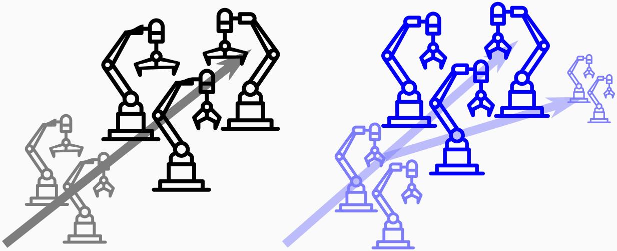

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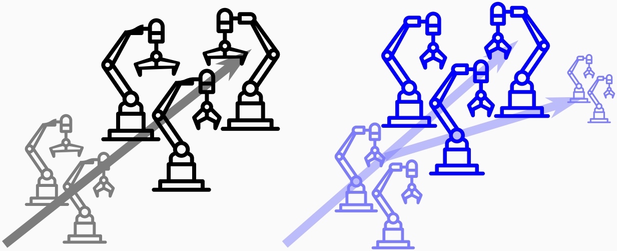

- How to ensure correctness/twinning in this setting?
- How to express twinning?

Digital Thread and Life-cycle Management

The Digital Twin Evolves in Tandem with the Asset

- Connects the designs, requirements and software that go into the system represented by the DT
- Connects the different phases of the system to the DT: design, development, operation, decommissioning, ...

Reconfiguration in the Operation Phase

- Behavioral drift: the twin's components need to be adjusted
- Structural drift: composition of components needs to change

Challenges

Challenge 1: Formalizing Properties

- How to express twinning?
- How to represent physical and digital twin?

Solution: Semantic Technologies and Ontologies

Challenge 2: Self-Adaptation

- How to adapt to changes in the physical twin?
- How to use semantic technologies for self-adaptation?

Solution: Use MAPE-K framework from robotics

Challenge 3: Digital Thread

- Can we express twinning over the digital thread?

Solution: Integrate, Record and Monitor into Semantic Twin

Semantically Lifted Programs and Digital Twins

Semantic Technologies

Triple-Based Knowledge Representation

Knowledge Graphs are a framework to (a) represent, (b) reason over, and (c) query domain knowledge and data.

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Peter hasChild Paul. Paul hasChild Maria.
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`hasChild` **some** (`hasChild` **some** `Person`)

subClassOf `GrandParent`

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Peter hasChild Paul. Paul hasChild Maria.
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OWL:

`hasChild` **some** (`hasChild` **some** `Person`)
subClassOf `GrandParent`

SPARQL:

```
SELECT ?x WHERE { ?x a GrandParent }
```

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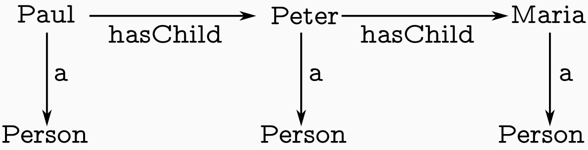

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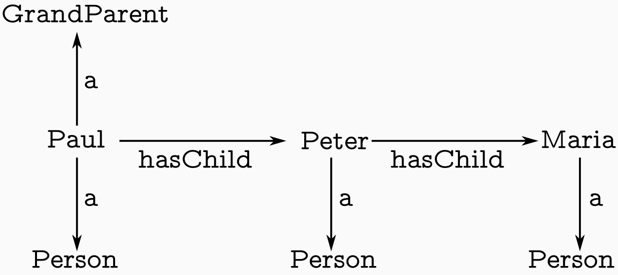

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A semantically lifted program can interpret its own program state as a knowledge graph and reflect on itself through it.

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$$\text{conf} \xrightarrow{\texttt{x} := 0} \text{conf'}$$

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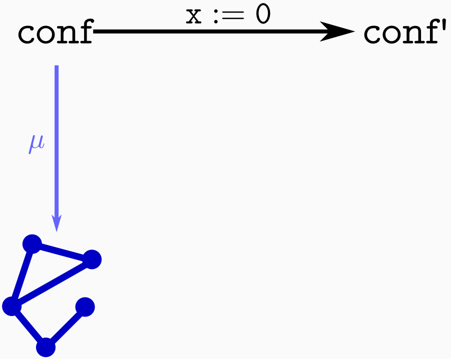

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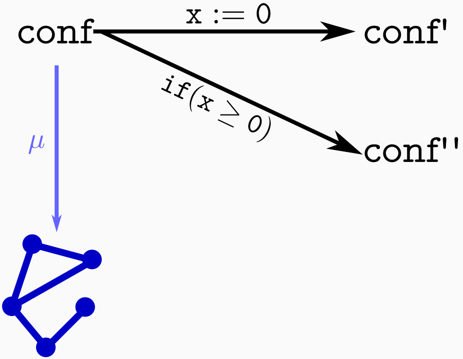

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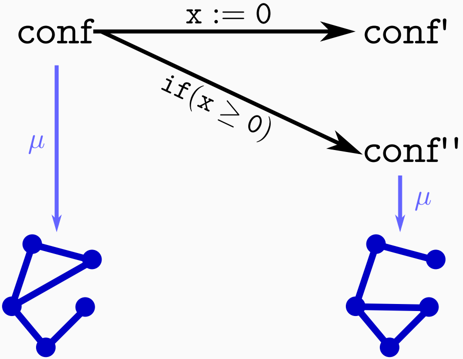

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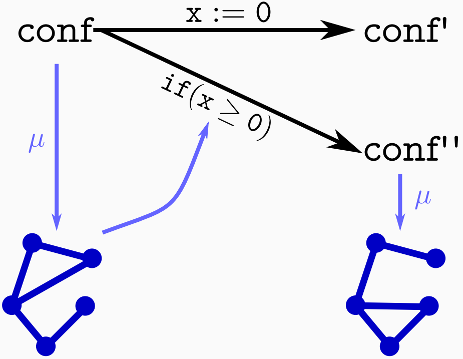

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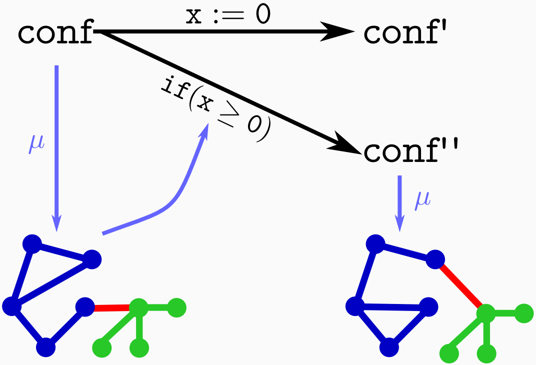

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Semantic Programming

```
class Platform(List<Server> serverList) ... end
class Server(List<Task> taskList) ... end
class Scheduler(List<Platform> platformList)
 Unit reschedule()
  List<Platform> l
    := access("SELECT ?x WHERE {?x a :Overloaded}");
  this.adaptPlatforms(l);
 end
end
```

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```

```
:Overloaded
 owl:equivalentClass [
   owl:onProperty (:tasks, :length);
   owl:minValue 3;
 ].
```

Knowledge Graphs and Asset Models

Asset Model

An asset model is an organized, digital description of the composition and properties of a physical asset.

Our Asset Model

For now: A knowledge graph describing the current structure of the physical twin.

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```
ast:w1 a ast:Wall. ast:w2 a ast:Wall.
ast:w1 ast:id 13. ast:w2 ast:id 12.
ast:w1 ast:leftOf ast:w2.
```

Checking the Twinning Property

Combining the Knowledge

- Export asset model of physical system as knowledge graph
- Export program state with simulators as knowledge graph
- Formulate constraints over combined knowledge

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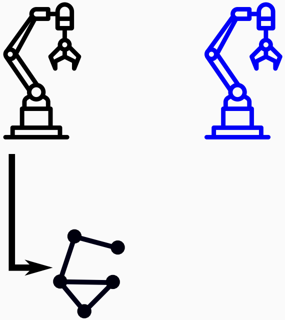

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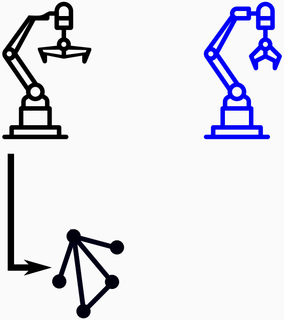

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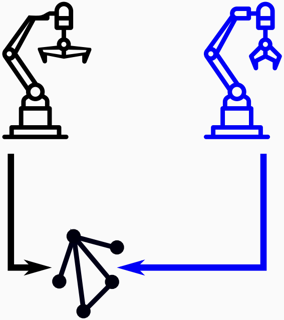

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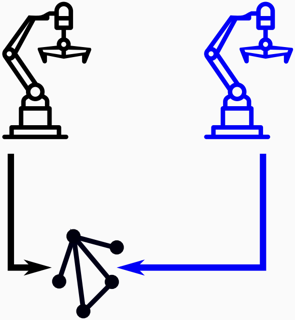

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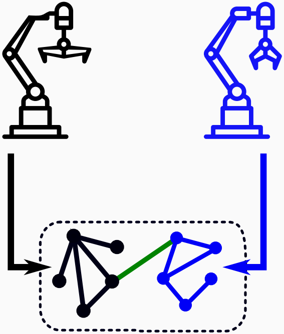

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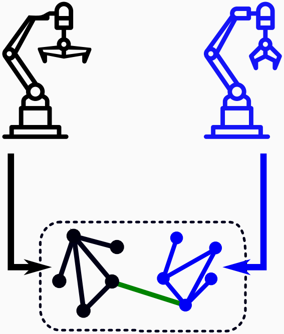

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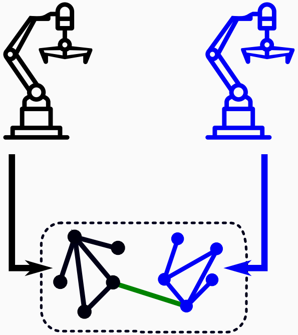

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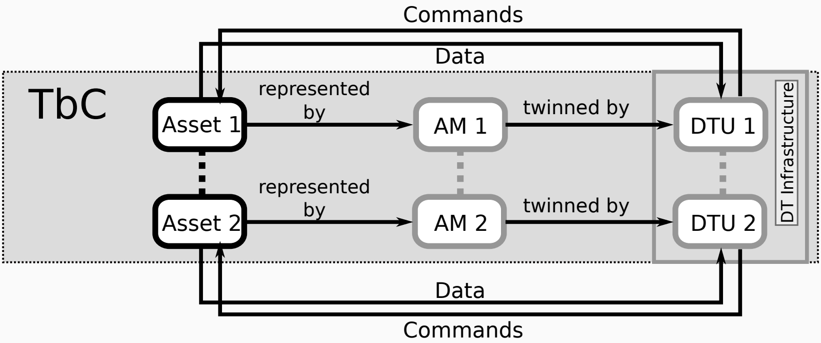

MAPE-K

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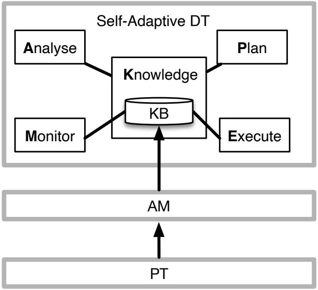
- A **K**nowledge component keeps track of information and goals for the self-adaptation loop:
- **M**onitor the situation
- **A**nalyze whether the situation requires adaptation
- **P**lan the adaptation
- **E**xecute the plan



Self-Adaptation (II)

Behavioral Self-Adaptation

Simulated (=expected) behavior of certain components does not match the real (=measured) behavior of the sensors.

- Monitor sensors
- Analyze the relation to simulation
- Plan repair by, e.g., finding new simulation parameters
- Exchange simulators or send signal to physical system

Reasons

- Sensor drift
- Modeling errors
- Faults
- Unexpected events

Self-Adaptation (III)

Structural Self-Adaptation

Simulated structure of digital system does not match real (= expressed in asset model) structure.

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We need to express the program structure, so we can *uniformly* access it together with the asset model. How to apply semantic web technologies on programs? ⇒ Semantical lifting.

Self-Adaptation (III)

Structural Self-Adaptation

Simulated (= lifted) structure of digital system does not match real (= expressed in asset model) structure.

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Semantical lifting is a mechanism to automatically generate the knowledge graph of a program state.

MAPE-K for Semantic Digital Twins

Monitoring Twinning

Monitor

Check whether all assets in production (`as:InProd`) are twinned (`dti:twin`) by some DTU (`dti:DTUnit`).

```
SELECT ?x { ?x a as:InProd.
  FILTER NOT EXISTS (?y a dti:DTUnit. ?y dti:twins ?x.)
}
```

Monitoring Twinning

Monitor

Check that all DTUs that exist are connected the same way as their PTs.

```
SELECT ?dtu { ?dtu a dti:DTUnit. ?dtu dti:twins ?asset.
  OPTIONAL(
    ?asset as:leftOf ?right.
    FILTER NOT EXISTS (
      ?dtuRight a dti:DTUnit.
      ?dtu dti:leftOf ?dtuRight.
      ?dtuRight dti:twins ?right.
    )
  )
}
```

Simple Twinning

Analyze

Both queries most return an empty set. Let their conjunction be denoted `SIMPLE`. If $\texttt{SIMPLE} = \emptyset$, then the system is simply twinned.

Planning

Plan creation and reconnection of DTUs according to query results. Eventually, run additional queries.

Execution

Retwin system: create DTUs, initialize them and reconnect if necessary.

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Digital Twin Reconfiguration Using Asset Models, Kamburjan et al. [ISoLA'22]

Temporal Twinning

Beyond Simple Twinning

- It is easy to see that $\square \mathtt{SIMPLE} = \emptyset$ does not hold.
- Additionally to twinning, one monitors the temporal property that within n time steps simple twinning is reestablished

$$m\text{−Change} \equiv \square\left(\mathtt{CHANGE} \rightarrow \neg\Diamond_{(0,m]}\mathtt{CHANGE}\right)$$

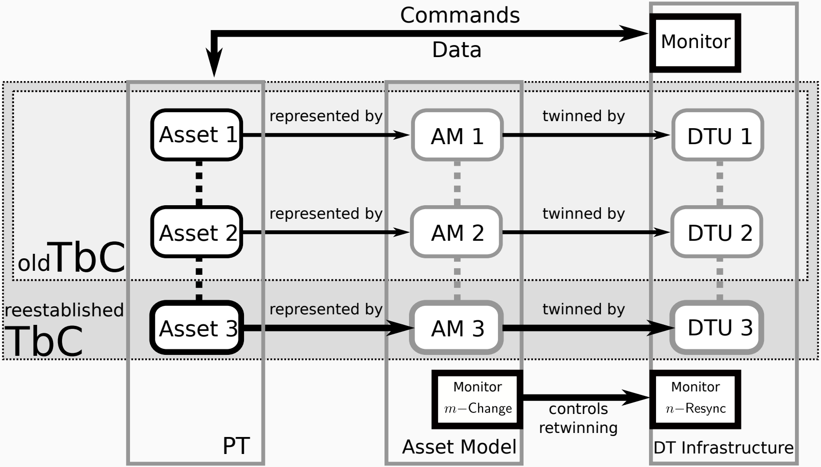
Twinning

Twinning takes some time, and the asset changes regularly – we must retwin faster than the asset model changes

$$n\text{−Resync} \equiv \square\left(\mathtt{SIMPLE} \not\doteq \emptyset \rightarrow \Diamond_{[0,n]}\mathtt{SIMPLE} \doteq \emptyset\right)$$

$$\mathtt{TEMP}_{m,n} \equiv m > n \land m\text{−Change} \land n\text{−Resync}$$

Monitoring Structure



Digital Thread

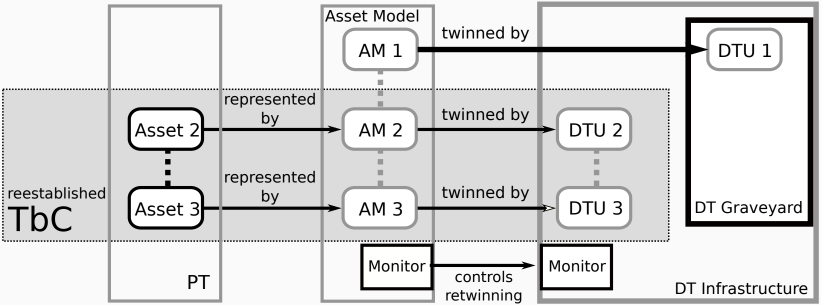
So far we checked the addition of assets, what about further operation recorded in the digital thread?

1. Build walls `as:w1` and `as:w2`
2. Build wall `as:w3`
3. Replace `as:w2` with `as:w3`
4. Decommission `as:w3`

```
as:w1 a as:Wall. as:w2 a as:Wall. as:w3 a as:Wall.
as:w1 a as:InProd. as:w2 a as:Decom. as:w3 a as:InProd.
as:w1 as:leftOf as:w3. as:w3 as:replaces as:w2.
```

Digital Thread

Idea: keep “old” DTUs, mirror structure of thread



General Observation

Digital Twin Infrastructure becomes more Thread-like

- Graveyard is twinning decommissioned assets
- Monitors are twinning requirements

Queries over the Digital Thread

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What is the wall left of whatever is in the place of wall `w2` now?

```
SELECT ?x {?x as:leftOf [as:replaces* as:w2]}
```

Queries over the Reflective Twin

Which reconfiguration are triggered by water damage?

```
SELECT ?reconf {
       ?a as:observed ?ev. ?ev a as:WaterDamage.
       ?d dti:twins ?asset. ?d dti:reconfiguration ?rcf.
       ?ev as:at ?dt. ?rcf dti:at ?dt.}
```

Twinning and the Digital Thread

A system has the simple temporal twinning property, if the DTU of every removed asset is moved to the graveyard. (TEMPSIMPLE)

```
SELECT ?x { ?x a dti:DTUnit.
  FILTER NOT EXISTS(
    ?x dti:twins ?asset. ?asset a as:Decom.
    ?asset as:removedAt [a as:Removal; as:at ?dt1].
    ?x dti:removal [a dti:Remove; dti:at ?dt2].
    FILTER ( microsec(?dt2) - microsec(?dt1) < 5*60*1000 )
  )
}
```

$$\mathtt{TEMP}_{m,n} \land \Box\big(\mathtt{TempSimple} \not\doteq \emptyset \rightarrow \Diamond_{[0,n]}\mathtt{TempSimple} \doteq \emptyset\big)$$

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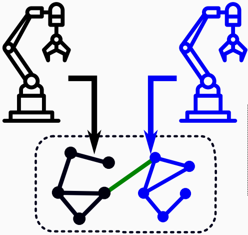

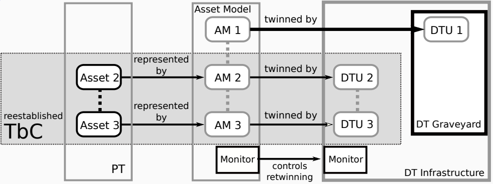

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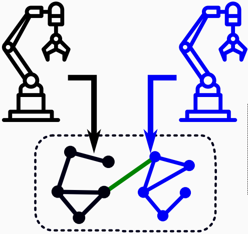

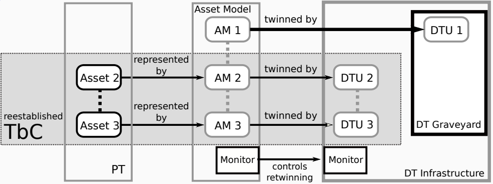

Thank you for your attention