The Role of Higher-order Models in Robotics and its Reasoning Challenges

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RobMoSvs

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RobMoSys' five levels of modelling

1. **Abstraction**: guidance for humans, by following harmonized interpretation of abstractions.
2. **Reuse & Flexibility**: reuse and customization of robotics software assets, via **data sheets**.
3. **Predictability**:
   composition is *correct by construction*.
4. **Automation**: automate labor-intensive stuff:
   Validation & Verification, code generation,...
5. **Autonomy**: models at run-time.
   self-configuration & -adaptation, explanation,...

What is "higher-order modelling"?

model:

- set of **entities** connected by **relations**.
- **data structure** for each entity & relation.

→ **property graph** (or "entity-relation" graph)

higher-order model:

- set of **relations** on top of other **relations**,
- with (partially ordered) **hierarchy** in the **semantics** of the relations.

→ one sees the hierarchy in the **directed** graph structure, and in the **properties** of the relations.

Relevant for RobMoSys' modelling levels 3–5.

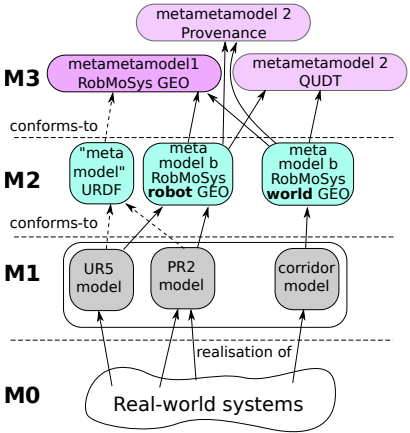
Added value higher-order modelling?

- **knowledge representation** of the domain:
  - data $\rightarrow$ **information** $\rightarrow$ knowledge
  - **composability** and **compositionality**:
    to combine pieces of knowledge in "the right way"
- **reasoning**: to explain, to generate, to monitor

- **sofware** brings *knowledge representation* too:
  - **configuration**: *gazillions* of "magic numbers" to be combined when composing components.
  - **coordination**: generate *task state machines* at runtime, because *gazillions* of contextual requirements require different **interaction behaviour** of components.

Major example

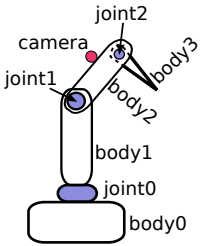
M0–M3 meta model of model-driven engineering

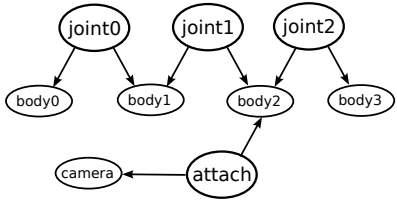


The **higher order** represented here is:

- M1–M3 relations are **relative**; "hierarchy" can be extended "upwards" indefinitely.
- level n models the constraints that must be satisfied in a model at level $n-1$.
- allows **translation** between (meta) models, for their **conforming** parts.
- typically, that knowledge is used by **humans** using a **tool chain**.
- dream of robotics: develop **robots** that can use that knowledge, themselves.

Robotics example: motion stack
Most abstract model: mereo-topology

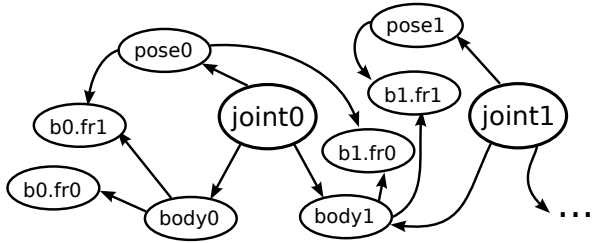




The **model** represents:

- **parts** in the model, and
- **connections** between those parts.

One more concrete level: motion constraint relation

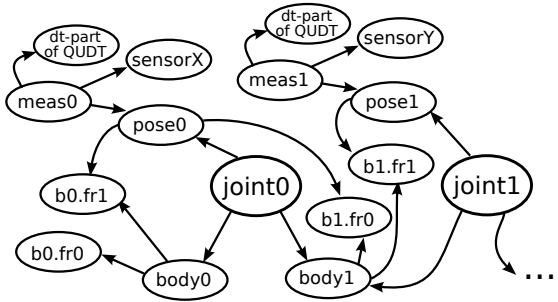


The extra higher-order **model** represents:

- joint is a **motion constraint** between robot's links
- at every moment in time, two links have a relative **pose** whose properties depend on the type of the joint constraint

→ mathematical constraints between positions on connected body points.

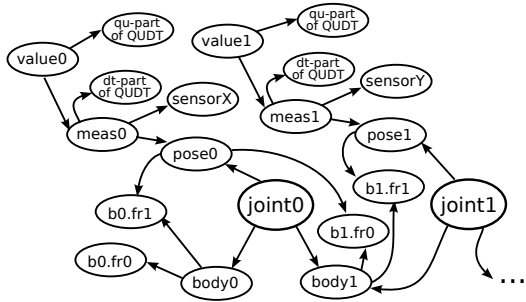
Yet one more concrete level: pose measurement type



The extra higher-order **model** represents:

- the pose is **measured** by sensors
- it has a **d**imension and **t**ype
- **QUDT** is a standard meta model for this purpose

Yet one more concrete level: pose measurement values



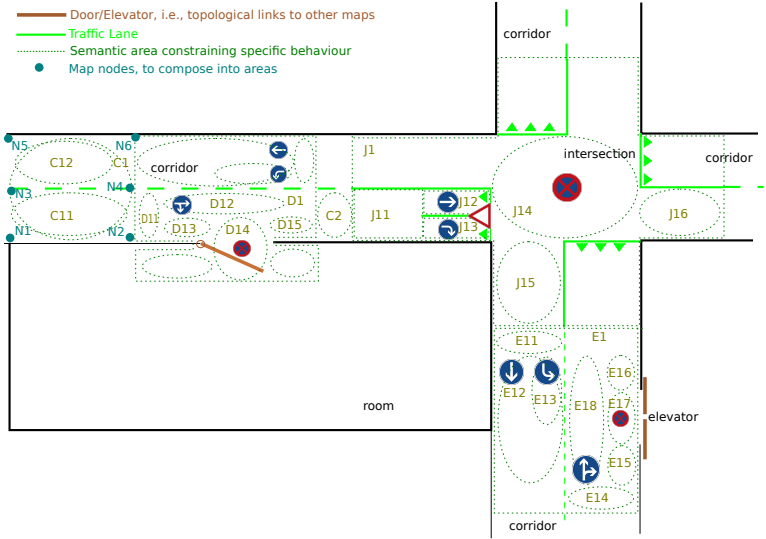
The extra higher-order **model** represents:

- measurement of pose gives **numerical values**.
- those **q**uantities have physical **u**nits
- **QUDT** is a standard meta model for this purpose

Queries on such higher-order models

- *raise an event when camera speed is below "motion blur" limit*
- *can my software components exchange velocity data with yours?*
- *if not, which software component can provide the missing translation between both coordinate representation?*
- *generate the composite kinematics solver when* `Arm_xyz` *is put on top of* `MobileBase_123`
- *generate a dynamics solver that adapts to a 1kHz torque control loop around it, and to the accuracy of the sensors*

Robotics example: semantic map



Queries on such higher-order models

- *raise event if robot is near high-risk area*
- *can my software component interpret all semantic tags relevant for a given task?*
- *if not, which software component can provide the missing translation between the map's semantics and my software components data sheet?*
- *generate the task graph to move from* `Area_xyz` *to* `Area_123`*, while maintaining safe behaviour against all expected other users of the building*

We're not there yet. . . !

Nevertheless:

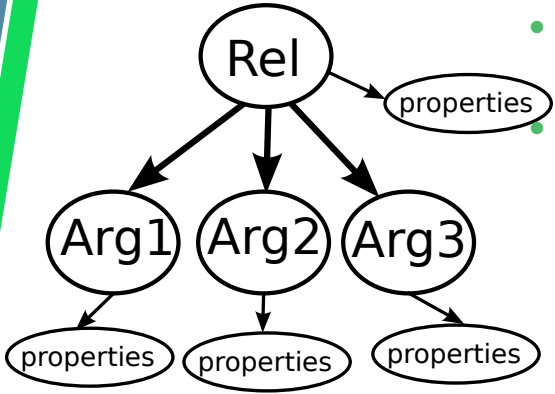
- problem investigated for **50 years** already. . .
- the **market pull** is tremendous. . .
- all **researchers** claim they provide solutions. . .

Why?

- mainstream focus: **sofware only**.
- higher-order modelling is **tough**;
  developing **query solvers** even more.
- software components: too limited **compositionality** via models.
- . . .

Mechanism of higher-order modelling

`Entity-Relation` models



- *entities* are the **arguments** in *relations*.
- supporting data structure: **property graph**: every node in the graph has:
  - a **property** data structure.
  - a **list of outgoing edges**.
  - a **list of incoming edges**.
  - a `Semantic_ID`: its own ID + IDs of its **meta model** + **list** of **meta meta model** IDs

Mechanism (continued)
Reasoning

- **query** is a property graph in itself:
  - sub-graph of **entities** one wants information about,
  - when constrained by specified **relations** in the graph,
  - and extra **constraint** relations introduced by the query.

  For example: *"Give all places on the map close to the robot, and observable by its sensors"*.
- **solver** base on **graph traversal**:
  - represents the **knowledge** required to travel through the graph in the "right way" to find the answer to the query.
  - is **also** property graph, of **higher order**!
- **state of the art**: close to nowhere, still...
  RobMoSys: develops **platform** infrastructure.

Major modelling errors

- using `is-a` instead of `conforms-to`.
  E.g.: a mobile robot *is not* a robot, but it shares a lot of the behaviour

- using *property* (`has-a`) instead of *attribute* (property of argument in relation)
  E.g.: a robot *does not have* a position value, because that is the property of a relation between the robot and its environment

- **reification** is not a *first-class citizen*:
  - every relation becomes an entity in itself

  $\rightarrow$ can become part of higher-order relation itself!

  Examples of "modelling" languages that fail here:
  UML, StateCharts, SysML, OWL, Prolog, Lisp,...

Developments in RobMoSys

Cgraph library (from `graphviz` ecosystem):

- efficient `C`-library for property graphs

→ **in-memory** reasoning possible.

- query formulation and graph traversal solving are **not** supported...

Application focus, for now:

- geometric world model, with semantic labels.
- kinematic and dynamic solvers, with control and estimation around it.
- semantic localization at "platform" level.

JSON-LD: identified as (non-exclusive!) *best fit* for purpose of serialisation and file format:

- supports `Semantic_ID` out of the box.

Conclusions

- robotics has **a lot of context**, hence higher-order modelling is a must.

→ surprisingly few results in that direction...

- modelling remains an **art**.
  querying and **solving** queries even more so!
  - especially for the **higher-order** models,
  - connected to **system-wide** dependencies.

→ those are where *the money* is!

→ **business models** feasible,
even on top of fully *open source* models!

Thank you for your attention