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Hierarchical Hypergraphs for Knowledge-centric Robot Systems: a Composable Structural Meta Model and its Domain Specific Language *NPC4*

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Abstract—Many robotics applications rely on *graph models* (that is, nodes and edges) in one form or another: perception via probabilistic graphical models such as Bayesian Networks or Factor Graphs; control diagrams and other computational "function block" models; software component architectures; Finite State Machines; kinematics and dynamics of actuated mechanical structures; world models and maps; knowledge relationships as "RDF triples"; etc. In traditional graphs, each edge connects just two nodes, and graphs are "flat", that is, a node does not contain other nodes.

This paper advocates the research hypothesis that *hierarchical hypergraphs* are better models than traditional graph models to represent the *structural* properties of systems: (i) an edge can connect *more* than two nodes, (ii) the attachment between nodes and edges is made explicit in the form of "ports" to provide a *uniquely identifiable* view on a node's internal behaviour, and (iii) every node can in itself be another hierarchical hypergraph. These properties are encoded formally in a *Domain Specific Language* (or "a meta model of a language"), called "*NPC4*", built with *node*, *port*, *connector*, and *container* as primitives, and *contains* and *connects* as relationships. These two relationships are key to the formal description of *topology*, which *complements* other key relationships in robotics systems such as *"is-a"* (behaviour) and *"has-a"* (composition, aggregation), which are already well covered by modelling languages like UML or AADL. The structural model described in *NPC4* form can be further enriched with additional *domain-dependent* constraints that define a more concrete Domain Specific Language (DSL).s *NPC4* introduces a particular "contains" primitive, the *container*, to support *overlapping contexts*, which is important in *knowledge-centric* robotics systems to model (i) various *levels of abstraction* in domains, (ii) "multiple inheritance" from (or rather "conformance to") different knowledge domains, and (iii) connecting one or more domain DSLs to the same *software infrastructure* in which they all have to be "activated".

Index Terms—Domain Specific Language, meta meta model, composability, structural modelling, knowledge representation

1 Introduction

Everywhere in robotics, graph-based structures (that is, compositions of "nodes" and "edges") show up as models of concepts, knowledge, software, and systems, to name just a few examples. Graph models are good at separating the *structural* and *behavioural* parts of a design, that is, the undirected graph represents which nodes interact with which other nodes, without describing the behaviour *inside* the nodes, or of the interaction dynamics *between* nodes. Below is a non-exhaustive list of examples in robotics, where *nodes*, *edges* and sometimes *ports* are the building blocks of the graph-based *structural* models. The Appendix provides more details about how the *structure* in each of the specific domains supports the

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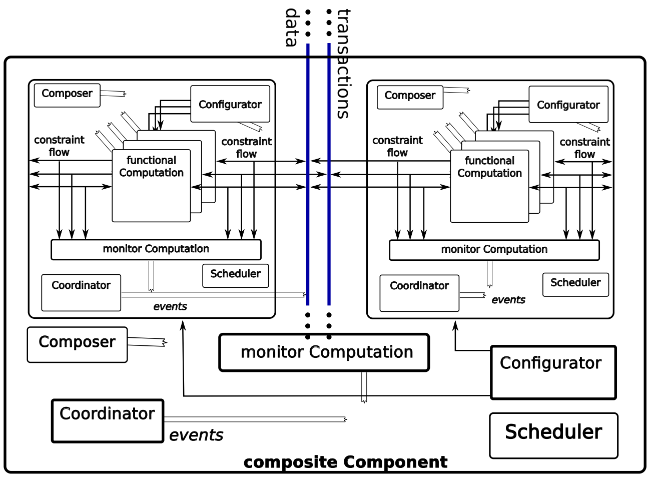

Figure 1: Structural model of a *composite component* software architecture [1]. *Nodes* represent software responsibilities; *edges* model relationships between data.

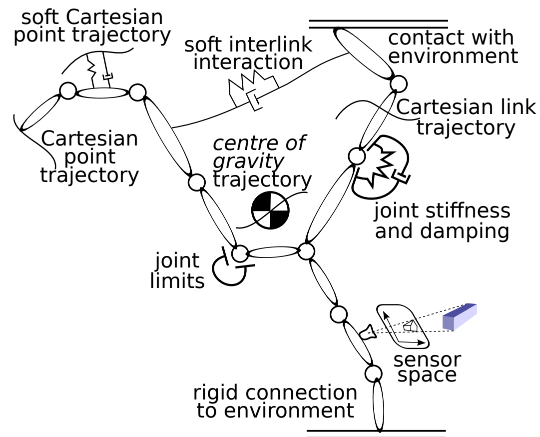

Figure 2: A generic tree-structured kinematic chain with possible task requirements on the chain's joints and links. *Nodes* represent actuated joints, rigid-body links, or a task's interaction dynamics (hard motion constraints, or soft "impedances"); *edges* represent (dynamics-less) connections between nodes.

domains' *behaviour*; the insight that the reader should get from this list of Figures and examples is that a quite limited number of modelling primitives suffice to support *all* structural aspects of these robotics sub-domains. The objective of the paper is to formalize this insight into a *Domain Specific Language* for the *structural* properties of systems; their behavioural properties are then still to be composed onto the structural model, by adding node and edge *types*, each with many different behavioural semantics. The concrete examples are:

- *software architectures*, as in Fig. 1;
- *kinematics and dynamics of actuated mechanical structures*, see Fig. 2.
- *Finite State Machines* (FSM), as in Fig. 3; a transition is structurally an edge that represents a relationship between two states (i.e., nodes), enriched with domain-specific behaviour dependent on the FSM formalism applied (e.g., guard conditions, events, priorities to which the transition is subject to, etc.);
- *probabilistic graphical models* such as Bayesian Networks or Factor Graphs, Fig. 4;
- *control diagrams*, such as the Cartesian position control scheme of Fig. 5, as well as other "data flow" computational models such as *Simulink* [2], where the nodes host functions (e.g. integrator and gain blocks), and the edge orientation indicates inputs and outputs (e.g. $\dot{x} = y$ or $\dot{y} = x$ for an integrator block);
- *knowledge representation networks*, such as the "semantic web";
- *web applications*, in which HTML5 [3] brings a significant change in the way that structure and behaviour are being separated in a clean but composable way.

All graph models above represent the *structure* of the interactions that are represented by their *edges*, and their *nodes* are the containers for the different kinds of *behaviour* that the model represents. Some models support *hierarchy* (i.e., a node can contain a full graph in itself), and some support *hyperedges* (i.e., one edge can link more than two nodes). Some models introduce the concept of a *port* (such as software models, Bond Graphs [4], or HTML5) as a "view" on a part of the internal state of the node it is connected to, and serving as an explicit "attachment point" for interactions via edge connectors.

The **central research hypothesis** in this paper is that the concept of the *hierarchical hypergraph* is a compositional representation to cover *all* the structures discussed above, particularly, via the *containment* and *connection* relationships. The formal version of this structural representation is the *NPC4* meta model; it conforms to the meta meta model of the mathematics of hierarchical hypergraphs, adding the semantics of system composition.

A *meta model* (or, modelling language) is a language with which to create concrete *models* of a system in a particular application domain or context. A *meta meta model* is a *domain-independent* "language" to support the creation of *domain-dependent* meta model languages, or *Domain Specific Languages* ("DSLs"). It is beyond the scope of this work to provide details on DSL concepts, therefore the reader can find further information in [5], [6], [7], [8], [9], while some examples of DSLs in robotics are [10], [11], [12], [13], [14], [15].

This paper's **refutable research hypothesis** is that *NPC4* provides:

- a *separation* between structure and behaviour;
- a *minimal* set of language primitives and relationships to describe the structural part of graph-based models that are relevant in the robotic domain;
- a *methodology* to make a new DSL by *only* having (i) *to specialize* the interpretation of *NPC4*'s primitives (node,

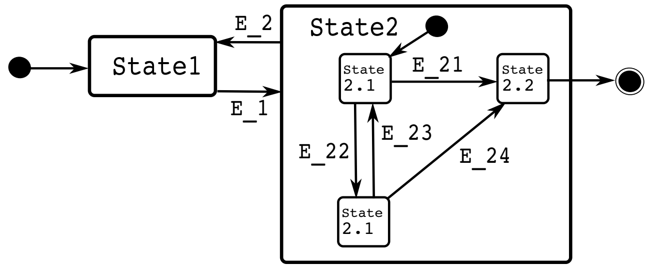

Figure 3: A hierarchical Finite State Machine. *Nodes* represent states, and *edges* represent state transitions.

port, connector, container) to the domain, and (ii) *to add* constraints to the *contains* and *connects* relationships.

The minimality concept pertains the expressivity of *NPC4*: each primitive and relationship has a specific role not covered by others; any additional primitive or relationship does not add expressivity in the structural model, but syntactic sugar to simplify the structural specification in some domains, that is, a derived DSL [16].

The validity of the presented approach is motivated by the large set of relevant examples that conform to the *NPC4* meta model; its refutation could come from showing that the above-mentioned goals are not reached (e.g., some primitives are redundant), or are already covered completely by existing modelling languages like UML or AADL, which are very prominent in the industrial practice [17].

The focus on only the generic structural aspects of robotics systems can hopefully lead to a step change in *reuse of software*:

- *reuse of syntactical parsing code*: the structure of a DSL is explicitly visible through the language's syntax, and since *NPC4* provides a common structural basis to DSL builders, they should be able to reuse a lot of the parsing software;
- *reuse of infrastructure code*: every DSL that is being introduced in a robotics system requires more support from the system's infrastructure code than only the realisation of the modelled domain functionalities, e.g., logging, messaging, debugging, tracing, and so on. *NPC4* provides all the "hooks" to connect these non-nominal software requirements too;
- *reuse of "Model-to-X" transformation tooling*: models are *declarative* specifications of domain functionalities, and inevitably needs to be *transformed* into code that supports turning the declarative specifications into procedural code, and basing different DSLs onto the same *NPC4* core simplifies reuse of such model transformation tools.

Overview. Section 2 explains the semantics of what this paper understands under the term "hierarchical hypergraph", since that concept is, surprisingly, not part of the mainstream literature. It also creates a fully formal language for hierarchical hypergraphs, in the form of a DSL or meta modelling language. The language is called *NPC4*, inspired by the first letters of its core *primitives* and *relationships*: `node`, `port`, `connector`, `container`, and, respectively, `contains` and `connects`. The `contains` relationship represents hierarchy, the `connects` relationship represents hyperedges. Section 3 discusses and formalizes the constraints and properties integrated into the *NPC4* language, while Section 4 illustrates its composability features. Section 5 revisits two of the use-cases introduced above in more details, explaining how *NPC4* can be used as the basis for their structural models, and the resulting benefits. Finally, Section 6 gives details on prior work and how the proposed *NPC4* can be seen as a step-forward regarding models standardisation in robotics.

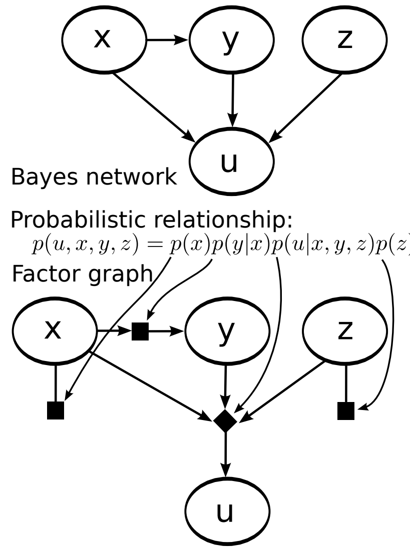

Figure 4: A probabilistic relationship and its corresponding *Bayesian Network* and *Factor Graph* representations. The Factor Graph is one of the few examples where *hyperedges* are *first-class citizens* of the graphical model; the advantage is visible in the figure: the Factor Graph can be linked one-to-one to the semantics it represents (i.e., the probabilistic relationship), while the mainstream Bayesian Network representation can not.

2 Hierarchical hypergraphs

This section proposes the adoption of *hierarchical hypergraphs* in the robotics domain, instead of traditional graphs, as its main structural model. The motivation is based on the list of examples in Sec. 2.1 that illustrate various ways in which the use of traditional graphs introduces erroneous ways of representing and reasoning about complex systems. The situation is critical since many users of graph models are not aware of these problems, or cannot formulate them by lack of an appropriate and semantically well-defined language; such a language, *NPC4*, is then introduced in Sec. 2.4.

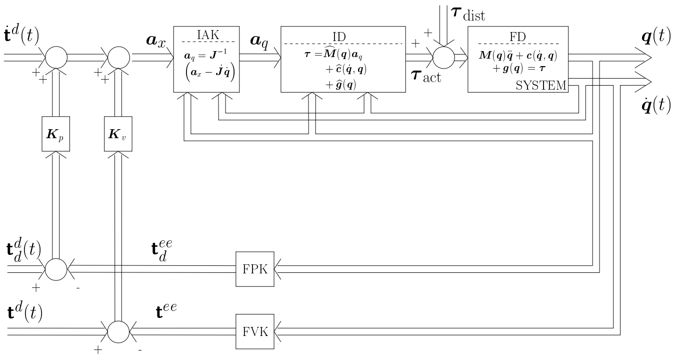

Figure 5: A generic Cartesian control diagram for position controlled robots. The *nodes* contain computations on variables in the diagram, and the *edges* represent (directed) transfer of such variables between nodes. *Hierarchy* is typically not represented explicitly, but *is* present in many control schemes, via the implicit structural primitive of *cascaded control loops*, that is, an "outer" control loop around an "inner" loop.

2.1 Motivations and bad practices

Traditional graphs have *nodes* and *edges* as model primitives, and most practitioners feel very comfortable with using them as graphical primitives for modelling. However, traditional graphs have a rather limited expressivity with respect to modelling the *structural* properties of a system design. The paragraphs below explain commonly occurring "bad practices" in using traditional graphs.

An edge can only connect two nodes, while many structural interactions are so-called *n-ary relationships*, that is, more than two (i.c., "n") entities interact at the same time, and influence each other's behaviour.

Obvious examples of n-ary relationships are "knowledge relationships", such a conditional probability in a Bayesian network Fig. 4. But also motion controllers of robotics hardware must deal in a coordinated way with all the links, joints, sensors, actuators, *and* their interactions via the robot's kinematic chain.

The structural model is flat, in that all nodes and edges in the model live on the same "layer" of the model. However, *hierarchy* has, since ever, been a primary approach to deal with complexity in design problems by allowing to interconnect various *levels of abstraction* when modelling a system.[1]

For example, a *kinematic* model of a robot structure might be enough for motion planning, but the *dynamics* of its actuators might be needed to design the robot's motion controllers. Since the actuators are mechanically connected to the kinematic chain of the robot, a hierarchical structural model would apply perfectly to support the separation between the kinematic and dynamic models of the same robot.

Also *knowledge relationships* are prominent examples of where the problem of flat structural models is very apparent: here, *hierarchy* is equivalent to *context*, that is, the meaning of a concept depends on the context in which it is used. Context is an indispensable structure in coping with the information in, and about, complex systems; in software implementations, this is most visible in how values of configuration parameters are to be determined.

A third prominent "bad practice" example of (too) "flat" structural models are the popular (open source) *robotics software frameworks*, like ROS or Orocos: they do not support hierarchical composition of software components, the consequence being that users always see all the dozens, or even hundreds, of nodes at the same time. This makes understanding, analysis and debugging of applications difficult. Further details will be presented in Section 5.

Edges have no levels of abstraction, and just serve as topological symbols representing the immutable, logical state of different nodes being "connected" or "not connected".

However, almost all of the use cases in the introduction have edges that can exhibit dynamics when opened up to a deeper level of abstraction; e.g., the communication channels between software components (time delays, buffering,...), the mechanical dynamics of joints and actuators in robotics hardware, and so on. The structure introduced in this paper advocates a clear and systematic rule: behaviour is *only* placed in nodes, at any particular level of abstraction of the model. When going to a more detailed level of abstraction, it *is* possible that behavioural nodes "show up" in a part of the model that was just an edge at a higher level of abstraction. For example, an ideal kinematic joint is a perfect constraint between interconnected links, but when going to a more detailed dynamical model level, behaviour will show up in the form of friction, or energy transmission dynamics inside the electrical actuator.

Interactions are uni-directional. Most modelling approaches use *directed* edges, that is, the graph assumes that each "partner" in an interaction can influence one or more other "partners", without ever being influenced itself by those partners in any way. Nevertheless, *bi-directional* interactions are the obvious physical reality: interactions, including man-machine interactions, exchange energy in both directions.

2.2 Primitives, relationships and their semantics

This section introduces a minimal and complete set of primitives and relationships to describe a semantically consistent structural model. The concepts of *hyperedges* and *hierarchy*, as key additions to existing graph modelling traditions, aim to prevent the implicit, domain-specific assumptions discussed in the previous section.

1. This paper deals only with hiearchy in *structure*; the complementary hierarchies in *behaviour* or *mereology* are already well modelled by the "is-a" and "has-a" relationships in languages like UML.

The core of the language are the **structural relationships** of `has-a`, `connects` and `contains` between the **model primitives** of `Node`, `Port`, `Connector` and `Container`. The semantic role of a `Node` is to host a behaviour, while a `Connector` describes the interaction relationship between the behaviour inside *multiple* `Nodes` by "connecting" them. Formally, a `Connector` realises an *hyperedge*, since the relationship is not *unary* but n*-ary*, and is un-directional by default (that is, unless explicitly constrained not to be so). In traditional graph modelling, a duality property exists between `Node` and `Connector`: both can be seen as *vertex* or *hyperedge*.

However, this symmetry disappears as soon as the *containment* relationship is introduced. In fact, the *hierarchy* concept is orthogonal with respect to the *hyperedge connection* concept. *Hierarchy* is expressed by the relationship `contains` applied to the `Node` primitive: a `Node` can contain a full hierarchical hypergraph in itself. The latter is semantically justified by observing that the hosted behaviour by the `Node` can be structurally represented as composition of internal `Nodes` and the interactions between them. Note that *composition* is a primary design driver of the proposed hierarchical hypergraph approach.

To achieve full expressiveness of the structural model, the `Port` is formally introduced as the third primitive in the language. A `Port` offers a specific *view* of a `Node`, exposing a specific part of a `Node`'s internal behaviour, and creates structure in the *connects* relationships across *hierarchy* levels. As a consequence, the `connects` relationship involves directly the `Port` primitive, and not `Nodes`, as it will be illustrated in the following section.

Finally, a primitive called `Container` provides a grouping feature, allowing to add extra semantic knowledge to a selected subset of primitives; such "grouping" is known under various names, such as: "context", "namespace", "scope", etc. In contrast to `Nodes`, `Containers` can overlap each other, in non strictly hierarchical ways.

2.3 Design drivers

The major design drivers to ground the *hierarchical hypergraph* concepts as a *Domain Specific Language* are *minimality*, *explicitness* and *composability*, as suggested in [18]:

Minimality. The model represents only *interconnection and containment structure*. It serves as a skeleton to represent the information about the structural model, but it does not make any assumption on the behaviour present in such a structure.

Explicitness. Every concept, and every relationship between concepts, gets its own explicit keyword:

- `Node` for the concept of behaviour *encapsulation*.
- `Connector` for the concept of behaviour *interconnection*.
- `Port` for the concept of *access* between encapsulated behaviour and each of its interconnections.

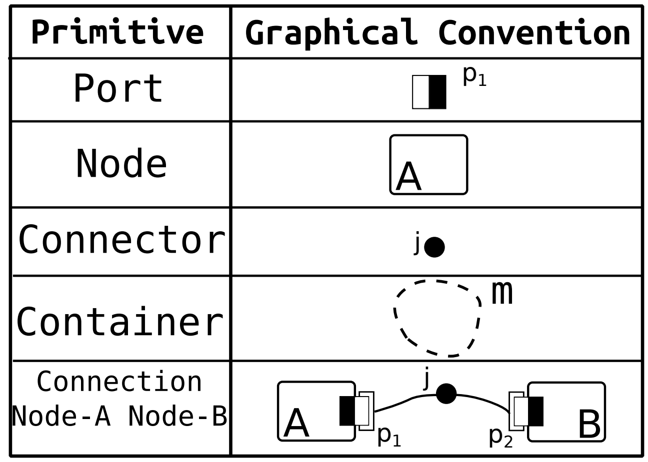

Figure 6: Graphical conventions to represent hierarchical hypergraphs: (i) `Port` is a square composed of two rectangles which represent (with respect to the `Node` to which the `Port` is attached) the internal (black) and external (white) docks; (ii) a `Node` is a rounded box; (iii) the `Connector` is shaped as a filled circle; (iv) the `Container` is represented as a dashed outline. The bottom row shows an example of two `Nodes`, namely *A* and *B*, connected by the `Connector` *j* attached to the external docks of `Ports` p_1 and p_2. The "clamps" on the docks appear if the docks have been linked to a connector.

- `Container` for the concept of *packaging* a model in an entity that can be refered to in its own right.
- `has-a` for the mereology relationship, that is, representing the parts *present* in the system, irrespective of the two structural relationships below.
- `contains` for the relationship of composition into *hierarchies*.
- `connects` for the relationship of composition via *interaction*.

Composability. The DSL is intended to represent only *structure*, and is, hence, *designed* to be extended (or *composed*) with *behavioural* models: it allows to connect other models to *any* of its own language primitives and relationships, *without* having to change the definition of the language (and hence also its parsers or other supporting software and tooling).

2.4 Formalisation into the *NPC4* language

The previous section provided an overview about the role and the motivations of the primitives and relations proposed in this work. This section turns this into a concrete DSL, the NPC4 *meta model for hierarchical hypergraphs*. A common approach in Model-Driven Engineer (MDE) [5], [9] is based on four different layers of abstractions, from **M0** to **M3**, briefly resumed as follows. The **M0** level refers to instances ("implementations") of a DSL model. The **M1** level comprises models that *conform to* [6] a *meta model*, defined on the **M2** level. Therefore, the *meta model* on the **M2** level specifies the

Primitive \ Primitive	`Node`	`Port`	`Connector`	`Container`
`Node`	contains	has-a	contains†	contains
`Port`	part-of	-	connects	is-contained*
`Connector`	is-connected (port)$^{+}$	connects	-	is-contained*
`Container`	contains	contains	contains	contains

Table 1: Overview of the primitives introduced by *NPC4* and the relative structural relationship allowed between them. The table reads has `{primitive-row}` `{relationship}` `{primitive-column}`, e.g. "a `Node` (can) contains a `Node`". Notes: (i) * it is not a relationship in *NPC4*, passive form; (ii) $^{+}$ it is not a formal relationship in *NPC4*, but informally a `Connector` is *indirectly* connected to a `Node` through a port; (iii) † as property of a *well-formed* `Connector`, see Sec. 3.1.

DSL in a formal way. Typically, each *meta model* can *conform to* several *meta meta models* at level **M3**. *NPC4* resides on the **M2** level, conforming to the (abstract and not yet formalized) **M3**-level concepts of hierarchical hypergraphs and structural system composition. It is obvious that multiple *meta models* on **M2** can coexist and can be composed[2] into new DSLs. In this cases, a new DSL *conforms to* one or more other meta models on the same **M2** level; a concrete example will be illustrated in Section 5.

In the remainder, the *textual* formalization of the language is discussed, while Fig. 6 shows the corresponding *graphical* conventions used in the paper; the latter are introduced only for illustration, and should not be considered as "the" formalization introduced in this paper. Table 1 provides an overview on the language core (which *is* "the" formalization), and Table 2 illustrates the DSL by means of the concrete example of Fig. 7.

`Identity` is given to all primitives by simple declaration:

$$\texttt{Node}: \ \texttt{node-B}, \texttt{node-X}, \ldots \quad (1)$$

$$\texttt{Port}: \ \texttt{port-p}, \texttt{port-x}, \ldots \quad (2)$$

$$\texttt{Connector}: \ \texttt{connct-i}, \texttt{connct-j}, \ldots \quad (3)$$

$$\texttt{Container}: \ \texttt{cntnr-m}, \ldots \quad (4)$$

Furthermore, let $\{\texttt{node}\}$, $\{\texttt{port}\}$, $\{\texttt{connector}\}$ and $\{\texttt{container}\}$ be the sets of all the declared `Node`s, `Port`s, `Connector`s and `Container`s, respectively.

`has-a`: a relationship between a `Node` and a `Port`. A `Port` can exist on itself (e.g., when it is still "floating" during the construction of a graph model in a development tool), but the graph model can only be "well-formed" (see Sec. 3) if every port belongs to exactly one node. Ports are those parts of a node through which (a *selected subset* of) the latter's behaviour becomes *accessible for interaction* to other nodes. So only statements of the following type make sense:

$$\texttt{has-a}(\texttt{node-B}, \texttt{port-p}), \quad (5)$$

and statements of the following type *do not*:

$$\texttt{has-a}(\texttt{connct-i}, \texttt{port-p}), \texttt{has-a}(\texttt{cntnr-m}, \texttt{port-p}).$$

2. This composition of DSLs is sometimes denoted as language *mixin*.

The inverse relationship `part-of` could be added to the model language, as syntactic sugar:[3]

$$\texttt{part-of}(\texttt{port-p}, \texttt{node-B}) \Leftrightarrow \texttt{has-a}(\texttt{node-B}, \texttt{port-p}). \quad (6)$$

`has-a`: a second relationship of this kind exists between a `Port` and a `dock`. The `dock` is a structural property of the `Port` that holds at most one connection with a `Connector`. Each `Port` has exactly two `docks`, one *internal* and one *external* with respect to the `Node` which owns the `Port`. The `docks` are true `Port` properties by design, therefore they are not considered as a primitive of the language. To distinguish with respect to the previous `has-a` relationship, the `dock` is uniquely referred by a *dot* (`.`) notation, that is:

$$\forall \texttt{P} \in \{\texttt{port}\}, \exists! \texttt{P.edock}, \exists! \texttt{P.idock} \quad (7)$$

with `edock` and `idock` being a port's external and internal dock, respectively. The `dock` property will turn out to be important later on, when well-formedness of connectors will be discussed in Sec. 3.

Fig. 6 shows the graphical convention of a `Port`, visualised as box divided in black and white rectangles; the former represents the *internal* `dock`, the latter is the *external* `dock`. The `has-a` relationship between `Node` and `Port` is visualised by placing the `Port` along the `Node` border.

`contains`: `Nodes` and `Containers` can contain other primitives, as represented by containment statements of the following type:

$$\texttt{contains}(\texttt{M}, \texttt{X}), \quad (8)$$

with `M` and `X` being a `Node` or a `Container`. The `contains` relationship brings *hierarchy* in the relations between `Node` and `Container` primitives.

Containment is a *transitive* relationship, so other containment relationships can be derived from the statements above; for

3. Informally, in this work the following sentences are equivalent of expressing an `has-a` relationship: (i) "a port belongs to a node", (ii) "a port is attached to a node".

Node: node−A, node−B, node−C, node−D, node−X, node−T
Port: port−q, port−r, port−p, port−n, port−u, port−s
Connector: connector−j, connector−i
Container: container−m

has−a(node−T, port−u)
has−a(node−X, port−s)
has−a(node−B, port−n)
has−a(node−B, port−p)
has−a(node−C, port−q)
has−a(node−D, port−r)

contains(node−A, node−B)
contains(node−A, node−C)
contains(node−A, node−D)
contains(node−T, node−A)
contains(node−T, node−X)
contains(container−m, node−A)
contains(container−m, connector−j)

connects(connector−j, port−q.edock)
connects(connector−j, port−n.edock)
connects(connector−j, port−r.edock)
connects(connector−i, port−p.edock)
connects(connector−i, port−s.edock)
connects(connector−i, port−u.idock)

Table 2: Full *NPC4* model of the example shown in Fig. 7.

example:

$$
\begin{aligned}
& \texttt{contains(container-m, node-A),} \\
& \texttt{contains(node-A, node-B)} \qquad (9)\\
\Rightarrow\ & \texttt{contains(container-m, node-B).}
\end{aligned}
$$

`connects`: a `Connects` relationship binds two or more nodes together, via an hyperedge (i.e. a `Connector`) attached to (an internal or external dock on) `Ports` on these `Nodes`. So, statements of the following type are semantically valid:

$$
\begin{aligned}
& \texttt{connects(connct-i,port-s.edock),} \\
& \texttt{connects(connct-i,port-u.idock).}
\end{aligned} \qquad (10)
$$

2.5 Composition

An extra keyword is introduced to indicate that all primitives *in* NPC4 can be compositions in themselves:

$$\texttt{composite} = \{\texttt{node,port,connector,composite}\}.$$

The recursion in this definition reflects the *hierarchical* property of containment in a natural way.

Secondly, the composition with *other, external* DSLs is realised via the following fundamental *design choice*, motivated by the proven way that, for example, XML-based meta models such as XHTML, SVG or JSON use: each primitive in a model *must* have the following meta data “property tags”, that explicitly indicate in which knowledge context (that is, using which meta models) they have to be interpreted:

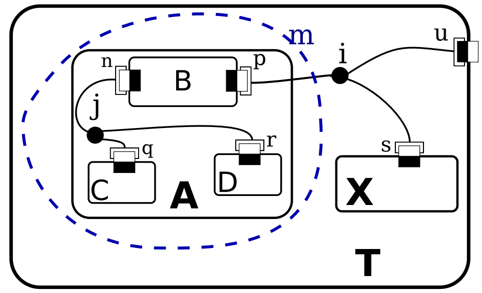

Figure 7: Generic example of a hierarchical hypergraph model. `Node` T is at the top of the hierarchy, and allows to refer to the whole model from within other models. `Nodes` A and X are contained by T, as is `Container` m; `Nodes` B, C and D are contained by A. `Connectors` i and j link `Ports` on `Nodes`. All `Ports` have `Connector` docks internal and external to the `Node` they belong to. `Container` m gives a context to `Node` A and its internals, but not to `Node` X or `Connector` i.

- `instance_UID`: a *Unique IDentifier* of any instantiation of the primitive concept;
- `model_UID`: a unique pointer to the model that contains the definition of the semantics of the primitive;
- `meta_model_UID`: a unique pointer to the meta model that describes the language in which the primitive’s model is written;
- `name`: a *string* that is only meant to increase human readability.

Such a generic property meta data allows to compose structural model information with domain knowledge by letting each primitive in a composite domain model *refer* to (only) the structural model that it `conforms-to` [6]; such composition-by-referencing is a key property of a language to allow for composability.

Finally, since *NPC4* is a language for structural composition, it deserves a separate keyword `compose` to refer to one or more of its possible composition relationships, namely `contains` and `connects`:

$$\texttt{compose} = \{\texttt{has-a}, \texttt{contains}, \texttt{connects}\}.$$

The motivation for the *explicitness* design driver is that (i) *each* of the language primitives can be given its own properties and, more importantly, its own extensions, independently of the others, (ii) it facilitates *automatic reasoning*[4] about a given model because all information is in the keywords (and, hence, none is hidden implicitly in the syntax), and (iii) it facilitates *automatic transformation* of the same semantic information between different formal representations. Such *model-to-model* transformations become steadily more relevant in robotics because applications become more complex, and hence lots of different components and knowledge have

4. This motivation comes from the objective to make the formal models useful not just to human system developers, at design time, but also to *robots themselves*, at *run-time*.

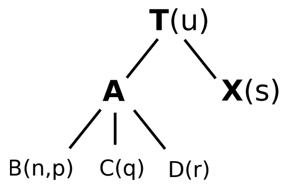

Figure 8: The containment tree of the nodes in Fig. 7. Each node carries its ports as arguments, since this information is required to check the well-formedness of `Connectors`.

to be integrated. Trying to do that with one big modelling language becomes increasingly inflexible,[5] because it will be impossible to avoid (partial) overlaps of the many DSLs that robotics applications will eventually have to use in an integrated way.

3 *NPC4* LANGUAGE CONSTRAINTS

The proposed *NPC4* language not only introduces *primitives* and *relationships*, but also *constraints* to guarantee both syntactic and semantic correctness. In this section these constraints will be discussed.

3.1 Constraints for structural well-formedness

Some constraints must be satisfied by composition relationships in a graph model to make sure that the model is **well-formed**.

There must be no "floating" ports:

$$\forall \mathtt{P} \in \{\mathtt{port}\}, \exists! \mathtt{N} \in \{\mathtt{node}\} : \mathtt{has\text{-}a(N,P)}. \tag{11}$$

The reason is that ports get their semantic meaning only from giving access to the behaviour that is contained in the node they belong to, so: without a node, a port has no meaning.

`contains` relationships on `Nodes` must result in a *containment tree*.[6]

A `Node` can contain other `Nodes`, but it must not contain itself. Furthermore, each node has one and only one "direct parent node" in a containment relationship. The reason for this constraint is as follows: since nodes are meant to represent behaviour, and since the containment hierarchy is meant to allow levels of abstraction in a system model, it makes no sense if two nodes that are separated at a higher level of modelling would contain the same behaviour node at a more detailed model level. In other words, behaviour cannot be shared by two nodes with different identity.

5. "Bad practice" experiences about relying on ever-growing modelling languages are unfortunately rather common in robotics: CORBA, UML, URDF,..., are just some of the better known examples where the initial benefits of "standardization" become hindrance to flexibility in composition, as soon as a couple of dozen "nodes" must be integrated, in ways that were not realised before.

6. Strictly speaking, a *forest*, that is a collection of disjuncted trees.

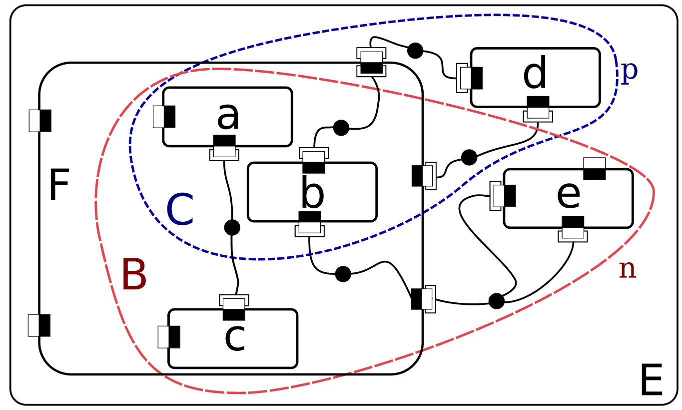

Figure 9: An example of a hierarchical composition in which *containment* does not follow a strict *tree* hierarchy *for containers*: the containers "p" (small blue dashes) and "n" (long red dashes) have some internal `Nodes` in common, with each other and with `Node` "A"; the containers "p" and "n" do not have ports themselves, in contrast to the `Node` "A". The *nodes* and their *connectors* do satisfy the *node containment tree* constraint.

As an example, Fig. 8 visualizes the node containment tree of Fig. 7. The *node* containment tree is unique for each *hierarchical hypergraph* and plays a relevant role on determining the validity of a `connects` relationship, as it will be discussed in the following paragraphs.

`contains` relationships of *containers* must result in a *directed acyclic graph*.

That means that a container (or a node) can have multiple "parent containers", and containers can overlap, but cannot contain themselves. This constraint is weaker than that for nodes, since containers are meant to represent knowledge, and knowledge can be shared indefinitely between nodes with different identities. An example is shown in Fig. 9, where `Containers` `n` and `p` overlap.

A `Connector` `connects` `Ports` on a joint containment tree.

The role of a `Port` is to provide a specific *view* on the `Node` that belongs to. In other words, the effect of the `Port` is to split the containment tree in two sub-trees, considering the `Node` as origin. The `Port`'s *internal dock* selects the "downward" subtree from that `Node`, while the external dock selects the "upward" subtree. Establishing a connection with a specific *dock* means to bound the relationship in the selected subtree, despite the other. For example, if a connector attaches to an internal dock of a port on a `Node`, all its other attachments must be to external port docks of `Nodes` that are contained in the given `Node`, or to other internal port docks of the same `Node`.

For the sake of clarity, Fig. 10 shows different model examples. The procedure to check this constraint is straightforward when starting from the `Node` containment tree: each of the

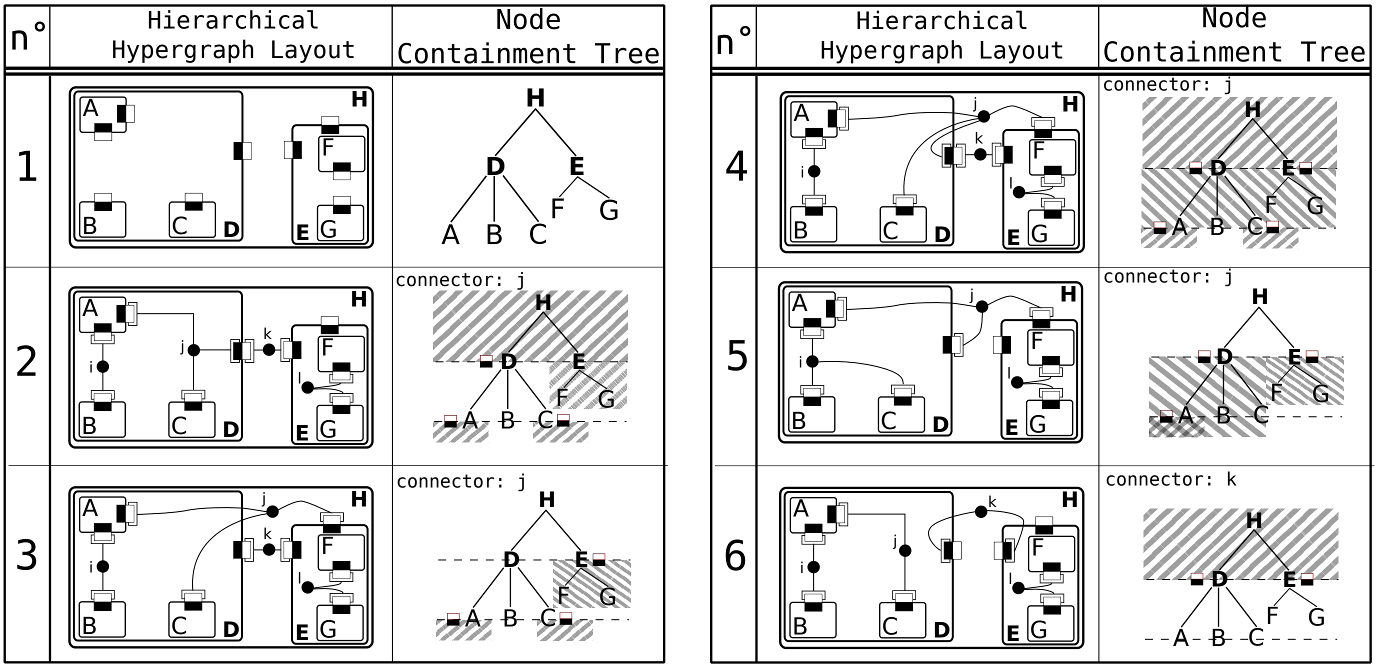

Figure 10: Different abstract examples of structural models defined with *NPC4*; both graphical layout and relative containment tree are shown. All the examples are based on the first model, which defines `contains` relationships only. The models differ by their `connects` relationship, and the containment tree is not affected by these changes. Examples (2) and (3) show well-formed models. In the associated containment tree, the `Connector` *j* is considered and the `Ports` involved in the relationship are indicated. In both cases, the resulting subtree obtained by pruning portions discriminated by the `Ports` is valid. The models (4), (5) and (6) are *ill-formed* because of the presence of a wrong `Connector`. In detail, in Model (4) the relation `connects(j,port-d.idock)` invalidates connections with `node-d` internals, thus the connection is not feasible. In example (5), `port-D.edock` excludes possible connections with `Nodes` `A`,`B` and `C`; since a `Port` in `A` is connected, the `Connector j` is not correct. The latter case (6) shows an intuitive case of connecting two `Nodes` through two wrong `docks` (`Connector k`).

ports involved in a connector prunes the `Node` containment tree in an downward and upward subtree depending on whether the `Connector` attaches to the `Port`'s internal or external dock, and the tree that remains after considering all involved `Ports` must still be *connected*.

The semantic meaning of this structural constraint is explained by observing an *ill-formed* example reported in Fig. 10. For instance, the `Connector j` in model 5 is semantically not correct, since it relates the node `Node E` with the whole `Node D`, but also with a `Node D` *internal* (`Node A`). Of course the `Node E` can have multiple kind of relationship with the `D Node`, but these are necessarily different relationships, as showed in the *well-formed* model 3. Different semantic meaning is represented by the `Connectors (j,k)` in models 2 and 3. In the former, `Node E` is in relationship with `D`, exposing a specific *view* on it (`Nodes A` and `C`). That is, the coupling `E-A` and `E-C` is indirect, since it considers explicitly the containment boundary `D`. In model 3, `Connector j` relates directly `Node E` with `A` and `C`, while `Connector k` is a completely unrelated relationship with respect to `Connector j`.

A *well-formed* `Connector` is contained in the *Lowest Common Ancestor* (LCA) of the `Nodes` involved. Considering the example in Fig. 7, a statement of the following type is semantically correct:

$$\texttt{contains(node-A,connector-j)}, \tag{12}$$

since `node-A` is *LCA* of `Nodes A`, `B` and `C`. This property is a consequence of a *well-formed* `Connector`, and it is not necessarily used to explicity define a model. In fact, a `Connector` instance is already fully defined by a list of `connects` relationship that involves that `Connector`. However, adding this extra information in a *NPC4* model can be useful as "checksum" during the validation phase. Finally, this `Connector` property helps the rendering of the hierarchical hypergraph layout.

As corollary, that implies that *every* graph model must have *at least one root Node*

$$\forall \texttt{C} \in \{\texttt{connector}\}, \exists \texttt{N} \in \{\texttt{node}\} : \texttt{contains(N,C)}.$$

The reason is that everything inside that root `Node` must have an identified context.[7]

7. This context need not be *unique*, since others can be added by composition.

When describing the design decisions behind a formal modelling language, it is not only important to identify and motivate the constraints that compositions in the language must satisfy, but also why some constraints have *not* been introduced in the language. In this paper, the following "non-constraint" is one of the fundamental *design choices*: the `contains` and `connects` relationships are *maximally decoupled*, in that one does not depend on the other. For example, even though `Nodes` "X" and "B" live at two different levels of the containment hierarchy, the connector "i" can still connect both (through a port).

Fig. 7 and Fig. 9 show examples in which a `Connector` is crossing a containment boundary; even when the boundary is defined by a `Node`, the `Connector` can leave without the *explicit* need of a `Port` on that `Node`.

While the decoupling is maximal, it is *not total*: connectors must take the `Node` containment hierarchy into account to some extent, that is, as described by the last constraint above.

In summary, *NPC4* does *not* introduce the (most often implicit) constraint of interpreting a *containment boundary* also as a *connection boundary*, since this should only be decided (explicitly) when domain specific semantics is being added to the domain-independent semantics provided by *NPC4*.

Another adopted "non constraint" design choice regards the *direction* over a `connects` relationship: no explicit direction is assumed, thus all the connections are *un-directional*. The direction is a property which belongs to the *behavioural* model, and not to the *structural* one: the constraint will be added in the specific domain of the *meta model*. A typical case is a FSM meta model, which will discussed in Sec. 5.

3.2 Constraints formalization

Section 2.3 introduced the *primitives* of the *NPC4* language, and the `contains` and `connects` *relationships* that can exist between these primitives. However, not all relationships that can be formed syntactically also have semantic meaning. This section describes some *constraints* already discussed in the previous section, but striving for formal completeness, by adding some obvious constraint relationships to the core semantics explained above.

Note that no `connects` relationships appear anywhere in the constraints on the `contains` relationships, and the other way around, which reflects the above-mentioned *orthogonality* of both relationships. Of course, when application developers add behaviour to a structural model of their system, they may introduce *extra* structural constraints, even between `has-a`, `connects` and `contains` relationships.

Constraints on primitives. The `UID` of every primitive must be unique:

$$\forall(\mathtt{X},\mathtt{Y}) \in \{\mathtt{node},\mathtt{port},\mathtt{connector},\\ \mathtt{contains},\mathtt{connects}\},\\ \mathtt{X.UID} = \mathtt{Y.UID} \Rightarrow \mathtt{X} = \mathtt{Y}.$$

Of course, these constraints hold for all three UIDs in the meta data of each *NPC4* primitive.

Constraints on `has-a`. As mentioned in Sec. 2.4, a `Port` can be floating during construction time, but a model having a port that is not `part-of` a `Node` is an *ill-formed* model. Furthermore, a `Port` *must* be `part-of` one and only one `Node`, that is:

$$\forall \mathtt{P} \in \{\mathtt{port}\}, \forall(\mathtt{N1},\mathtt{N2}) \in \{\mathtt{node}\},\\ \mathtt{has\text{-}a(N1,P)},\mathtt{has\text{-}a(N2,P)} \Rightarrow \mathtt{N1} = \mathtt{N2}.$$

The previous statements affects other relationships too, as it will be shown in the next paragraph.

Constraints on `connects`. The constraints in this section realise the *well-formedness* of the connection relationships, that is, about which kind of structural interconnections are possible. Recalling from Section 2.4, the `Port` has exactly two `docks`, one *internal*, and one *external*. Each such `dock` is constrained to have only one `Connector` attached, that is:

$$\begin{aligned} & \forall(\mathtt{C1},\mathtt{C2}) \in \{\mathtt{connector}\}, \forall \mathtt{P} \in \{\mathtt{port}\}: \\ & \mathtt{connects(C1,P.idock)}, \\ & \mathtt{connects(C2,P.idock)} \\ \Rightarrow\ & \mathtt{C1} = \mathtt{C2} \end{aligned}$$

$$\begin{aligned} & \forall(\mathtt{C1},\mathtt{C2}) \in \{\mathtt{connector}\}, \forall \mathtt{P} \in \{\mathtt{port}\}: \\ & \mathtt{connects(C1,P.edock)}, \\ & \mathtt{connects(C2,P.edock)} \\ \Rightarrow\ & \mathtt{C1} = \mathtt{C2} \end{aligned}$$

Furthermore, the *well-formedness* of the `Connector` (discussed in Sec. 3.1) can be formally expressed as follows:

- given `C` is the `Connector` to be validated;
- given the sets of internal and external `Ports`, p_{ci} and p_{ce}, defined as:

$$p_{ci} \triangleq \{p \in \{\mathtt{port}\} \,|\, \mathtt{connects(C},p\mathtt{.idock)}\}$$
$$p_{ce} \triangleq \{p \in \{\mathtt{port}\} \,|\, \mathtt{connects(C},p\mathtt{.edock)}\}$$

- then, $\forall p_i \in p_{ci}$, $N_i \in \{\mathtt{node}\}$ s.t. $\mathtt{has\text{-}a}(N_p, p_i)$ holds, $\forall p_j \in \{p_{ci}\} - p_i$, `C Connector` is valid if $\mathtt{contains}(N_p, p_j)$ holds, and the following condition holds
- $\forall p_e \in p_{ce}$, $N_i \in \{\mathtt{node}\}$ s.t. $\mathtt{has\text{-}a}(N_p, p_e)$ holds, $\forall p_j \in \{p_{ce}\} - p_e$, `C Connector` is valid if $\mathtt{contains}(N_p, p_j)$ does **not** hold.

Constraints on `contains`. The constraints in this paragraph realise the *well-formedness* of the containment relationships of `Nodes`, that is, about which kind of hierarchies, or "composites" are possible.

First, the fact that *every* primitive *can* be a `composite` in itself is expressed:

$$
\begin{aligned}
&\texttt{composite} = \{\texttt{node}, \texttt{port}, \texttt{connector}, \texttt{composite}\},\\
&\quad \forall \texttt{C} \in \{\texttt{composite}\}:\\
&\qquad \exists \texttt{n} \in \{\texttt{node}\} \lor \exists \texttt{c} \in \{\texttt{connector}\}\\
&\qquad \lor \exists \texttt{d} \in \{\texttt{composite}\}:\\
&\qquad\quad \texttt{contains(C,n)} \lor \texttt{contains(C,c)}\\
&\qquad\quad \lor \texttt{contains(C,d)}.
\end{aligned}
$$

Every `contains` relationship can only be defined on *existing* `Nodes` and containers:

$$
\begin{aligned}
&\forall \texttt{c} \in \{\texttt{contains}\},\\
&\quad \exists (\texttt{X},\texttt{Y}) \in \{\texttt{node},\texttt{container}\}:\\
&\qquad \texttt{c(X,Y)}.
\end{aligned}
$$

And finally, there *always* exists at least one `Node` at the top of a `contains` hierarchy:

$$
\begin{aligned}
&\forall \texttt{X} \in \{\texttt{node},\texttt{connector},\texttt{composite}\},\\
&\quad \exists \texttt{T} \in \{\texttt{Node}\}: \texttt{contains(T,X)} \lor \texttt{T=X}.
\end{aligned}
$$

This latter constraint is a *very strong* one, that is imposed for one and only one reason: every structural model should have an explicitly identified *context*. In other words, the meta data of the top `Node` must be made rich enough to understand the semantics of *everything* it `contains`, even when the model is deployed in a running system. There can be *more than one context* for each composition, which is in agreement with the design objective of composability: several context containers can be put around any existing model, and/or a composite can *conform to* more than one meta model. The top `Node` need not have any `Port` attached to it, so that it reduces to just a *container of meta data*.

4 MODELLING WITH *NPC4*

This section briefly discusses some structural features of the proposed solution.

4.1 Structure for supporting software

Many domain models use only traditional graphs, with `Nodes` and edges, while this paper's hierarchical hypergraph model splits the "edge" primitive in two new first-class primitives: "port" and "connector". The motivation for this choice is to allow not only more precise *domain* semantics *if needed*, but also a more flexible *infrastructure to support* a domain model with *software*. For example, by using ports to log and visualise data exchange between `Nodes`, or to count the number of interactions (statically as well as during run-time), or to make graphical development tools in which selections have to be made on which internal behaviour of `Nodes` to connect to, and so on.

Recall also the other motivation of this paper with respect to *hierarchical composition*: at a certain level of abstraction of a system model, a port might be a completely passive part of a system model, that is, without behaviour of its own, while more behaviour appears when going to a deeper level of abstraction in the system part represented by that port. A typical example is communication: two `Nodes` connected with communication middleware send and receive data through socket ports, at the application layer, but when going inside such a socket at the level of the operating system, lots of activity becomes visible: packet composition, encoding, timestamping, and so on. Much of that activity is "infrastructure" code for the higher level of abstraction, but this papers approach allows to connect all these things together, over different levels of abstraction.

The third software-centric motivation for the presented model pertains to the introduction of the *container* primitive: it *carries no behaviour*, but is used to model *information influence* of "higher" contexts[8] on "lower" `Nodes`, ports and connectors. More precisely, the container model primitive is needed *to store meta data*, such as: unique identifiers; references to the modelling languages in which the `Nodes`, ports or connectors inside a container are expressed; references to ontologies that encode the semantic meaning of the model (hence indicating, among other things, which configuration values to use for all model parameters); version numbers; etc. One particularly useful case is to introduce containers to store the *composition model* of the sub-system that is embedded within its internal context.

4.2 Behaviour on deeper *levels of abstractions*

In the proposed structural *meta model*, the *hierarchy* concept is applied to `Node` and `Container` primitives only. Allowing `Ports` and `Connectors` being hierarchies on themselves would violate the design choice that only `Nodes` carry behaviour.

However, in practical cases `Ports` and `Connectors` may manifest behaviour, if a *deeper level of abstraction* is considered. A concrete example arises in the attempt of model a software system involving two computers: what was first a simple shared data structure (i.e., a "`Connector`") in the centralized version now becomes a full set of cooperating "middleware" software components in itself (i.e., a composition of `Nodes`, `Connectors` and `Ports`). In short, modelling the distribution explicitly boils down in introducing a deeper levels of abstraction.

In such cases, it is possible to apply a systematic *model-to-model* transformation to obtain an alternative model, as a *composition* of the original *NPC4* model and a separate *NPC4* model of the `Port` (or `Connector`) internals. Fig. 11 illustrates two examples which expands `Port` and `Connector` respectively. In both cases `Port` and `Connector` have been modelled as a simple `Node`, which already enables the

8. Or scope, namespace, domain, or whatever terminology has been used to represent this container concept.

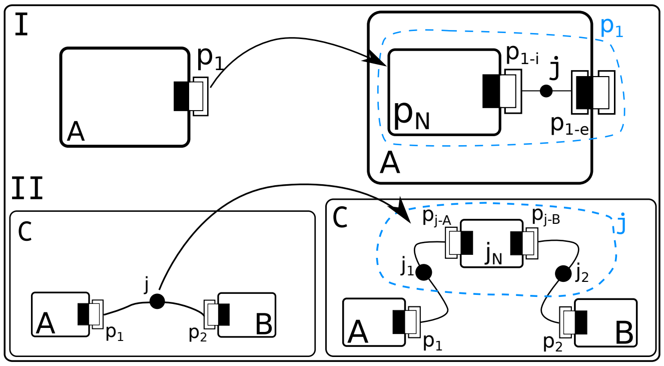

Figure 11: Examples of possible model-to-model transformations to describe a deeper level of abstraction. The first example (I-right) shows a solution to model behaviour on a `Port` primitive (I-left): `Port` p_1 is expanded in a `Node` p_N contained in `A` (original owner of p_1), while an internal `Connector` establishes a *view* over the same `Node`. The containment tree changes only internally to `A`, thus the change is compliant with the original model. Not necessarily but useful, p_1 refers to a `Container` in the transformed model, such that the original semantic information is preserved (and it is possible to retrieve the original model). The second example (`II`) shows a similar case, but considering the `Connector j` as target of the transformation.

hierarchy feature. Furthermore, a `Container` may be added to preserve the knowledge over the original model. As a remark, this property is offered by the *composability* feature of *NPC4*, considered as one of the primary design drivers of the language.

In conclusion, modeling a deeper level of abstraction is always possibile, but the described structural models differs.

5 Examples

This section gives concrete examples on how the meta model language *NPC4* can be used in existing and new meta models for robotic DSLs. These models must conform to the *NPC4* meta model from the structural part. Thus, the following rules to design the DSLs are used, in accordance with the "composability" design driver (Sec. 2.3) behind *NPC4*:

- give new, domain specific *names* to the *NPC4* primitives and/or relationships.
- add domain specific *extra semantics* to the *NPC4* primitives, relationships and constraints.

The provided example DSLs focus on the NPC4-*related* structural part, rather than defining full fledged DSLs. As examples *finites state machines* and *component architecture models* are chosen, since both models are present in many robotics applications. The examples illustrate that both models use the *hierarchical hypergraph* as are core compositional structure. Furthermore, the DSLs are exemplary designed to be *internal DSLs* embedded into JSON [19]. Thus, they have to conform to the syntax requirements of JSON. A JSON Schema file is used to check if the textual description of a model

```
{
  "states" : [
    "lcsm", "active", "inactive"
  ],
  "contains" : [
    { "parent": "lcsm",
      "children" : ["inactive", "active"] }
  ]
}
```

```
Node: lcsm, active, inactive

contains(lcsm, active)
contains(lcsm, inactive)
```

Table 3: A snippet of a possible DSL for FSM, hosted by a JSON document. Below, the same hierarchical structure described with *NPC4*.

is syntactically correct or not. However, the methodology on how to make a DSL based on the NPC4 *meta model* does not depend on JSON or any other tool chain. Additional examples on how to adapt the the *NPC4* methodology to other domains are briefly discussed in the Appendix.

5.1 Finite State Machines

FSMs are this paper's primary example, because they have simple and familiar semantics, with a big part of it reflected in their structural model. There are many different FSM "dialects", because, despite a rather large harmonization in the structural models, the behavioural parts of the various FSM DSLs do still differ. From a structural point of view, FSMs are defined as a set of `states` linked with `transitions`, with the constraint that each transition *connects* only two states.

This section discusses how an FSM DSL can be built with *NPC4*, and uses a so-called *Life Cycle State Machine* ("LCSM") as a concrete illustration. Fig. 12 gives a graphical picture, Tables 3 and 5 give textual JSON [19] versions of the *domain*-centric model, without and with behaviour respectively, while Table 4 gives the *NPC4*-centric "full" version of it.

LCSMs are common software components to coordinate the "life cycle" of other software component instances, from when they created from their "platform resources" (memory, CPU, I/O), till they are ready to provide their "capabilities" to other components; the *configuration* of, both, resources and capabilities is a major "behaviour" of a LCSM. A real-world example of such a LCSM is the motion control of all the joint actuators in a robot: only when, both, the platform resources and the capabilities have been properly configured, the component is ready to "run", that is, to actuate the robot's motors based on commands from a control component.

The component may be paused from its running state, that is, it is fully ready to provide its service (immediately, without

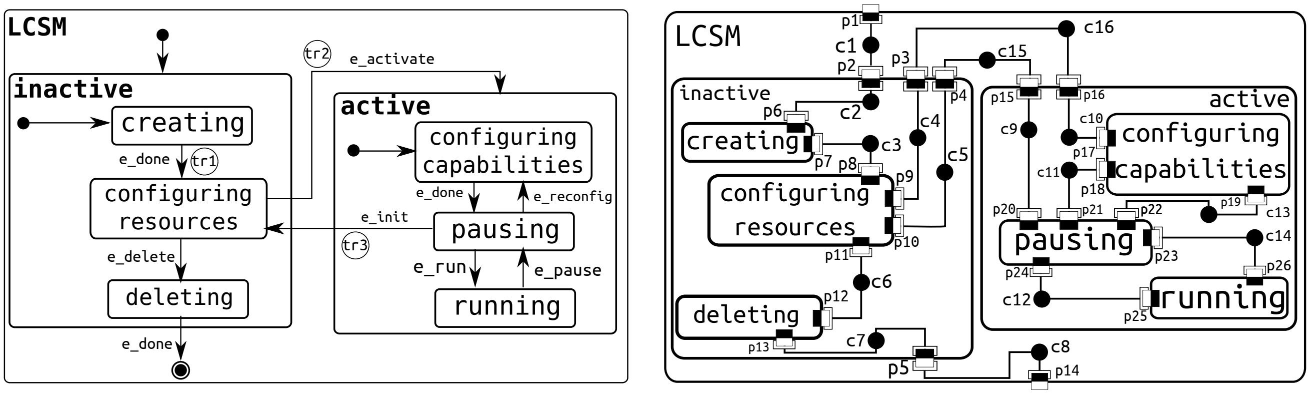

Figure 12: Life Cycle State Machine model (LCSM) of a generic software entity as an FSM model (UML flavour) on the left, and its Structural Model as Hierarchical Hypergraph on the right. `states` are represented as `Nodes`, while `transitions` as *Port-Connector-Port* patterns formed by two `connects` *NPC4* relationships. cX and pX are *instance_uid* of `Connector` and `Port`, respectively.

any further configuration), but for one or another application-dependent reason, the service is not actually delivered, yet. In the above-mentioned example of motion control, the operator might have pressed a "motion freeze" button.

It is beyond the scope of this paper to model "the" correct LCSM, but it has just been introduced in this text to serve as a familiar example of a commonly occurring FSM model.

The whole FSMs structural part of a LCSM can be modeled straightforwardly by the above-mentioned approach as follows:

- `states` are represented by *nodes* in *NPC4*;
- `states` can be hierarchical, with a *strict tree structure constraint* in the `contains` relationship;
- `transitions` are represented by `Connector` relationships, with the extra constraints that the transitions are always (i) *directed*, and (ii) only connecting *exactly two* states. The latter constraint is fully structural, while the direction constraint belongs to the *behavioural* part of the DSL.
- transitions between hierarchical levels are allowed, so this structural property of FSMs requires no extra *NPC4* constraint.

There is no explicitly visible concept of `Port` in FSM DSLs, but ports are needed nevertheless, in all software infrastructure with which an FSM model is stored and executed.

Fig. 12 gives, on the left, the traditional "domain-only" view on a LCSM, while the part on the right gives some examples of how ports are needed to attach the mentioned "infrastructure" structure and behaviour:

- `Ports` model the structural crossing of a transition across each level of hierarchical depth of states, Fig. 12. Such `Ports` are connected only to one connector in the same hierarchical level. Since the port belongs to a `Node`, the port can be attached to two connections, one *internal* and one *external.* For each hierarchical level crossed, a connector contained by the crossed hierarchical scope must be defined. The latter is due to the constraint that `connects` relationship is applied only between a `Connector` and a `Port`, and not between `Ports` directly;
- `entry` and `exit` functions of states are *behavioural* primitives of a state, which are "pointed to" from the ports where that behaviour is structurally located in the FSM, that is, there were the corresponding "incoming" and "outgoing" transitions connect with a state.
- the `initial` and `terminal` state primitives of FSM DSLS are just other cases of states, hence requiring nothing more than the addition of a new *named primitive* in the FSM DSL. The only difference is that the encompassing state must hold the function ("behaviour") that transitions to and from those states "at the right moment"; the latter behaviour is often a "semantic deviation point" between different FSM DSLs.

Since the FSM meta model conforms to [6] the hierarchical hypergraph meta meta model, the resulting concrete structure of the LCSM is described with *NPC4* primitives (Fig. 12, on the right).

- `states` and the hierarchical relationship is directly preserved into a `Node` hierarchical structure (tree) (see example Table. 3);
- `transition` as *port-connector-port pattern*: a simple (not inter-level) transition is structurally equivalent of a composition of two `connects` relationship (see Tab. 4);
- `entry` and `exit` points as connection between one parent and some of its child nodes, making use of the same *port-connector-port* pattern.
- *inter-level transitions* have a similar *structure*, but maybe a different *behaviour*, in various FSM DSLs,

Note that FSMs have different types of inter-level transitions, with possibly different behaviour semantics, while being indistinguishable from a structural point of view. For instance, the

```
{
  "states" : [
    "active", "creating", "
        configuring_resources"
  ],
  "contains" : [
    { "parent" : "active",
      "children" : [ "creating",
        "configuring_resources"
      ]
    }
  ],
  "transitions" : [
    { "type" : "transition", "id" : "tr1",
       "src": "creating",
       "tgt": "configuring_resources" },
  ]
}
```

Node: active, creating, configuring_resources
Port: p7, p8
Connector: c3

contains(active, creating)
contains(active, configuring_resources)
has−a(creating, p7)
has−a(configuring_resources, p8)
connects(c3, p7.edock)
connects(c3, p8.edock)

Table 4: On top, a snippet of a FSM model taken from the LCSM example (see Fig. 12), with JSON support. The model conforms to a FSM meta model, which it conforms to *NPC4*. On bottom, a *NPC4* code snippet which describes the structure of the FSM model above, with emphasis on the non-interlevel transition between the two states.

transition indicated with *tr2* in Fig. 12 (left) connects a state from an "deeper" level of containment to a state at a "higher" level, while the transition *tr3* does the opposite. Both have have analogue structures, i.e., chains of the *port-connector-port* pattern, defined as $\{c4, c16, c10\}$ and $\{c5, c19, c9\}$, respectively. However, for *tr3* the structure is fully defined by the transition itself, while *tr2* only defines $\{c4, c16\}$: the connector $\{c10\}$ is given by the `entry` point defined in the *active* state. The latter observation confirms a major invariant design decision of this paper, that the structure of the transition is decoupled from its behavioural meaning in the particular domain meta model.

In summary, *NPC4* provides a set of primitives to describe the graph representation of an FSM DSL, simply by adding domain-specific constraints. The structure provides the necessary attachment points to host behavioural policies of various FSM dialects [20]. A similar procedure can be applied to other domains already mentioned in Section 1.

```
{
  "states" : [ "lcsm", "active", "inactive" ],
  "contains" : [
    { "parent"   : "lcsm",
      "children" : ["inactive", "active"] ,
      "entry"    : "inactive" },
  ]
}
```

Node: lcsm, active, inactive
Port: p1, p2
Connector: c1
contains(lcsm, active)
contains(lcsm, inactive)
has−a(lcsm, p1)
has−a(inactive, p2)
connects(c1, p1.idock)
connects(c1, p2.edock)

Table 5: An extended version of the FSM model snippet in Table 3. Below, its relative structure described with *NPC4*. The emphasis is on the definition of the entry point of the composite state and the reflected changes on the graph structure. Changes has been highlighted. The full visual representation is shown in Fig. 12.

5.2 Component architecture models

Several benefits are possible from the adoption of a hierarchical hypergraph structure to describe a component-based software architecture. In the robotics domain, there is a large number of functionalities that must be integrated in an overall architecture, often deployed into reconfigurable components connected each others. Several middlewares offer such a capability, among which ROS, Orocos, YARP, CLARAty [21], [22], [23], [24]. These frameworks offer complementary (and sometime alternative) features regarding different aspects of the robotic system, such as real-time components, communication services, run-time configuration, deployment system and others. It is a common practice to build a software infrastructure choosing not one, but several middlewares to better adapt to specific needs. For instance, Orocos enables real-time activity containers, while ROS is more popular among the robotics community when different functionalites are to be deployed in multiple machines. Therefore, a robotic application is often a heterogeneous integrated system.

To show the potential of the proposed *NPC4* language, this section considers a concrete software application. The chosen use-case pertains to an application where a fleet of mobile platforms, equipped with camera, are exploring an unknown environment automatically, storing the collected information in a centralised database. The functionalities required for such applications are developed in a component-based fashion using ROS and Orocos middleware; some components are deployed on a centralised server, others are deployed locally with respect to the mobile agents. Among the latter, some components have

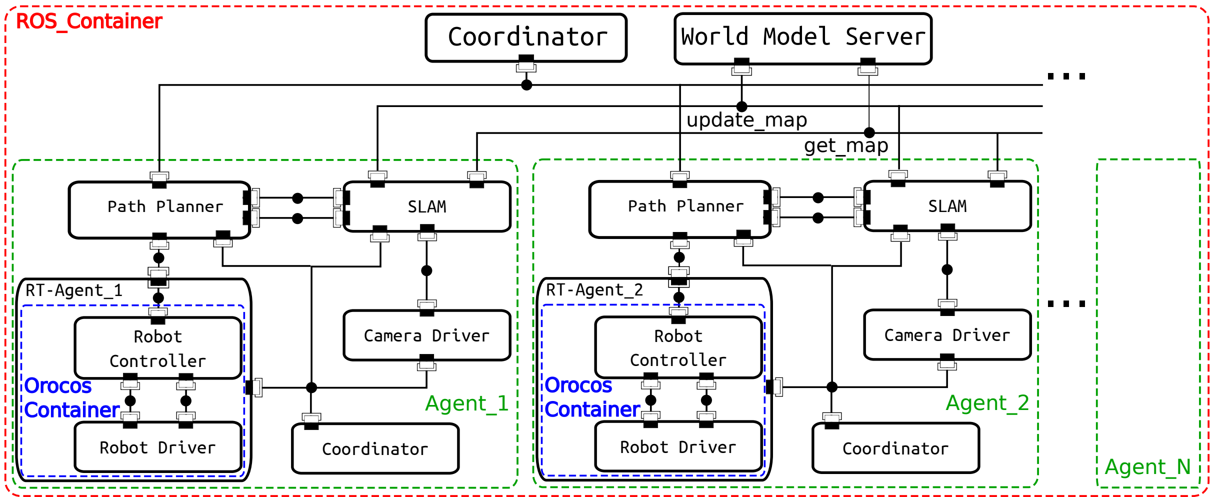

Figure 13: *NPC4* graphical representation of the *structure* of a component-based architecture for an automated environment mapping application. For the sake of clarity, the graph is not exhaustive: most of the `IDs` primitives are missing, as well as some connections and nodes required to provide complete functionalities. The *coordination* component assigns goals on the location to inspect to different agents. Each agent decides autonomously the path from its current pose to the goal. During the navigation, the outcome of a *SLAM* algorithm is used for both navigation and mapping purposes. This information is stored in a *world model* component, which is also used for the navigation of each agent. As a remark, the *world model* can be a graph-based database as well. Each agent has several software components running on-board; such information is marked with a specific container (green). A subset of those have real-time requirements, mostly those components regarding the "low-level" motion stack of the agent itself. These components are deployed in an Orocos process, indicated with the `Node` *RT-Agent_1*. The same node is also contained by a `Container` that states the interpretation in terms of middleware mapping reported in Table 6. Resuming, `Containers` are used to attach additional knowledge about the role of the components, that is where they are deployed, or to which middleware they belong. Furthermore, the remain components could be further expanded. For example, ROS nodes can contains other software components, so-called *nodelets*, which conform to the ROS component model, but their activity is deployed into *threads* and not *OS processes*.

real-time requirements, such as motion control functionalities. Thus, Orocos middleware is preferred, otherwise ROS is chosen. The architectural *structure* expressed in *NPC4* is shown in Fig. 13. Discussion of the "optimality" of the given architecture is beyond the scope of the example; the focus is on presenting the mapping between structural primitives and behaviour (or functionalities), reported in Table 6.

The role of the `Containers` is fundamental and non-traditional in this context, since it allows to attach additional information, such as grouping components in accordance with the hardware that is hosting the functionality, or the grouping of components that have to be configured together on the basis of the same system knowledge. Therefore, a first benefit given by a structural description is to provide different *context-dependent* views of the same architecture, concerning both off-line and run-time information. This enables, for example, the usage of common tools to visualize the architecture graphically. Tools provided in the middleware are not sufficient: for instance, ROS *rqt_graph* can only represent ROS-nodes, but not components from other frameworks, mainly due to the lack of a formal model description.

A second benefit is given by the possibility to solve queries over the software infrastructure, decoupled from the implementation of the middleware adopted. Relevant queries are the ones that validate the correctness of the model, for instance to verify a proper component connectivity. The previous can be done by checking the `Connector IDs`, which represent a specific data-stream (e.g., ROS-topics) and the extra directivity constraint given by the `Ports` connected to it. Only the extra constraint is necessary to accomplish a complete query that crosses the boundaries of the frameworks. In short, it is possible to build test tools on the *NPC4* structural model, avoiding solutions based on a single framework functionalities. Obviously, a necessary requirement is the existence of the integration functionality between the middleware, which must be modeled as well. In fact, the software integration often regards only the functionalities; the components are *hidden* behind an interface layer. Separating and modeling the structural parts avoids information hiding that regards only the functionalities. Furthermore, it is possible to link and chain these queries to the existing tools. As an example, information on the nodes and connectors contained in a ROS container can be retrieved online through the commands *rostopic* and *rosnode*.

A third advantage regards the code generation required for the deployment of the component into activity containers (OS processes or threads) provided by the different middleware. This is a popular issue tackled by the community so far, and toolchains to support it already exist, [25], [26], [27]. An approach based on *NPC4* is the following: from a structural *NPC4* model and additional knowledge associated to it, the

NPC4 Primitive \ Middleware	`Orocos`	`ROS`
`Node`	Component	Node
`Port`	Data Flow Port, Configuration Interface, Service Interface	Publisher, Subscriber, Service Interface, Actionlib Interface
`Connector`	Connection Policy, Service Name	Topic, Service, Action
`Container`	TaskContext, Component Packages	Packages

Table 6: *NPC4* primitives applied to ROS and Orocos functionalities, applied in the example of Fig. 13. A structural primitive in *NPC4* offers an attachment for multiple functionalities or behaviours, that must be interpreted accordingly the extra constraints imposed by different framework domains. For instance, in both middleware a port item has directivity as extra constraint related to the behaviour that represent (e.g., ROS: pub/sub, Orocos: input/output ports). As a remark, the proposed mapping describes up to a certain *level of abstraction*. For instance, `Ports` can be further expanded to represent a buffer policy on the incoming data.

purpose is to generate deployment files targeted to both middleware, that is ROS *.launch* and Orocos *.cpf* deployment files. Figure 14 shows few code snippets of this solution applied to the architecture of Figure 13. However, similar results are possible with existing toolchains; it is beyond the scope of this paper to compare these and provide specific details on the approach described; indeed, the purpose of the presented example is just to hint at the potential of the *NPC4* language in the structural facets of a model-driven engineering approach to system development.

6 Related Work

Support for *hierarchical hypergraphs*, including *ports*, as *first-class citizens* in the model is a rare exception. Among the examples discussed in Section 1, only FSMs, Factor Graphs and HTML5 have them in their models, and then only implicitly. Nevertheless, hierarchical, port-based, multi-node interactions are common in all engineering disciplines, as major modelling instruments to deal with complexity. Most practitioners in the field of (robotics) system design are often not *aware* of the extent to which their modelling languages and tools restrict their flexibility in modelling the designs of their systems.

An intrinsic limitation is present in *control diagrams*: the directed edges in, for example, *Simulink* [2] diagrams, can only represent input/output interactions between computational nodes, which prevents a "downstream" computation to influence the behaviour of the "upstream" nodes; saturation of a "block" or "channel" being one of the simplest and common examples of this problem.

Nevertheless, there are other computational tools, like *20Sim* [28], that do not oblige their users to use only uni-directional interactions, since they are based on the so-called *Bond Graph*-based modelling primitives [4], [29], [30], [31], that allow to represent the physical un-directional ("non-causal") energy interaction of dynamical nodes.

The opposite of the later problem also occurs: *directed arrows* are used in graphical notations while the represented interaction is really bi-directional, hence resulting in semantically misleading or too constraining models. For example, the probabilistic information in Bayesian networks *does* "flow" in both directions along a directed edge. Also in this context, *hierarchical* models have been adopted [32], [33], [34], [35] because of the complexity of integrating "local" and "global" features in sensor data, and of combining them with the knowledge available about the objects whose sensor features the system can observe.

Unfortunately, most of robotics projects with a high software engineering focus *do not have* explicit structural *models*, since they provide *only source code*. At best, "models" are only used as non-formalized means of documentation, to be understood by the human developers, but not by the robots themselves during their run-time activities, nor by software tooling to support (semi) automatic code generation. There are a few exceptions that (i) provide explicit formal models (for example, Proteus [36], or OpenRTM [37], [38]), and (ii) support hierarchical hypergraph models implicitly. Example of use of those models are Matlab/Simulink or 20Sim, the ROCK toolchain for Orocos [22], [39], [40], [25]. None of those, however, support the full flexibility that the hierarchical hypergraph Domain Specific Language (DSL) of this paper provides, to model the structural aspects of complex systems. This restriction becomes a more and more important design bottleneck in robotics, since modern robotic systems are increasingly depending on *run-time use of knowledge*, and the "flat triple spaces" that are standard in common RDF or OWL based [41] semantic web approaches to knowledge representations [42] are difficult to understand when growing, hence difficult to maintain, adapt, reason with, and compose. The latter problem, more particularly, is caused by the lack of support for *structural hierarchy* as a first-class primitive in OWL or RDF,[9] which makes it unnecessary hard to formalize knowledge *about* the knowledge encoded in OWL/RDF relationships or constraints, since such `contains` or `connects` relationships must be added explicitly in each OWL/RDF-based DSLs.

The example described in Section 5.2 shows practical advantages of the separation between the structural model

9. They *do* support "is-a" behavioural hierarchy.

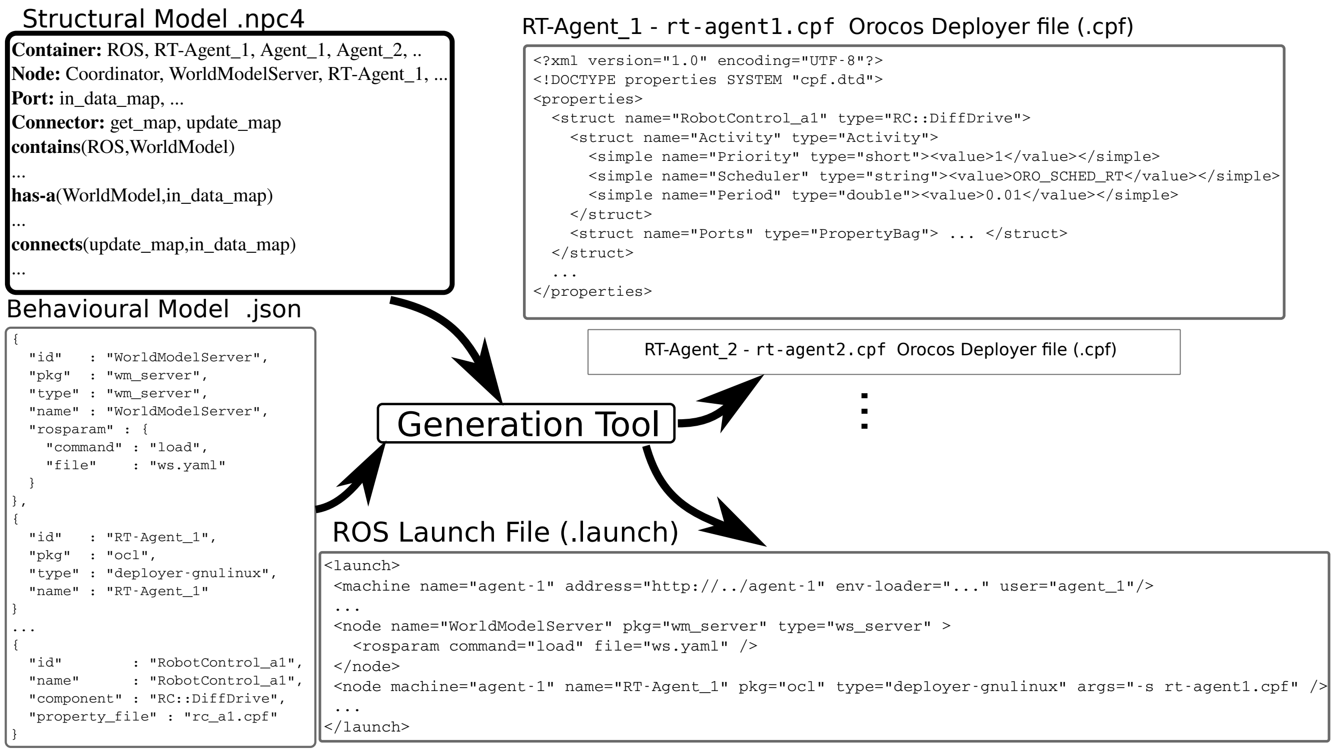

Figure 14: Conceptual overview of a code generator that creates deployment files of a component-based architecture in Figure 13. The illustration is not exhaustive regarding the models in example. Also, only the deployment information is considered. A structural *NPC4* model (textual representation, top-left) is compiled with the behavioural model (bottom-left), in JSON format. The outcome are a single ROS *.launch* file (bottom-right) and an Orocos deployment files (top-right) for each Orocos nodes (real-time components running on each agent). An `id` metadata links the behavioural information to the relative *NPC4* primitive. The remain knowledge is interpreted accordingly the associated `Containers`. For instance, for the `WorldModelServer` a single entry `<node>` is generated in the *.launch* file, since it belongs to a *ROS Container* (Figure 13). Names, parameters and other middleware-dependent information are extracted from the behavioural model. For each Orocos node (composition of Orocos components) is generated an entry in the *.launch* file plus the relative *.cpf* to deploy the Orocos process. Furthermore, `Containers Agent_j` indicate on which hardware the components are deployed, generating the relative information in the `.launch` file (`<machine>`).

and the behaviour (or functionality). In literature, several works tackled the deployment of complex and heterogeneous system architectures. The ROCK toolchain [25] is a practical effort to bridge MDE techniques and Orocos functionalities. A similar effort has been done in [26], having OpenRTM-aist [37] as backend middleware. The RobotML [27] DSL extends these principles, providing support to multiple middlewares in its toolchain. These solutions are based on existing modeling frameworks, such as the Eclipse Modeling Project [43]. However, the presented work differs from the mainstream approaches: instead of providing a solution that binds to a specific **M3** tool, a mathematical generalisation is provided such that the same structural model can be used for different purposes. Concretely, the *Component-Port-Connector* (**M2** model) of the *BRICS Component Model* [44] conforms to the *NPC4* meta model. However, the versatility of *NPC4* has been shown in Section 5: the structure of a component-based model (Section 5.2) and a FSM model (Section 5.1) are the same. Such a structural equality can be exploited, because of the existence of common operations; for example, in the rFSM [14] implementation [45], over the 60% of the code pertains to managing nodes and connections (states and transitions), while only the remaining 40% implements the concrete behavioural engine.

This work also contributes to language-oriented software development [46], [47] by means of composition of multiple DSLs. In detail, [48] provides a terminology to distinguish between different forms of language composition, and the derivation of a new DSL that structurally conforms to *NPC4* can be described by using that terminology (Section 5.1): firstly, the *NPC4* primitives and relationships are specialized with additional constraints, and this step is called *language restriction* or specialization; secondly, a behavioral model is attached accordingly, leading to a *language unification*. Therefore, the *NPC4* promotes a development process based on *extension composition*, that is the specialization of multiple DSLs that work together, each one addressing a different aspect of the system (structural, behavioural, functional, etc.).

Also the different design phases of a DSL development (decision, analysis, design, implementation, deployment) are discussed in literature; *NPC4* provides the structural primitives that are required to support the development of DSLs [16].

In summary, separating and standardizing the *hierarchical hypergraph* structure from the attached behaviour has a promising impact on the development of systems in the robotics domain.

7 Conclusions

What is the minimal set of primitives and relationships, to cover all use cases of structural composition in robotics applications?

This was the main research question that the authors tackled for almost a decade, motivated by the drive to realise a step change in the reuse of "infrastructure code". Several robotic frameworks have been developed in the last years, and all of them have quite overlapping needs with respect to the structural composition of the functional primitives they offer, yet no common designs or models are shared, let alone code.

This paper advocates the use of the *NPC4* language, as *the* meta model to represent *port-based* and *container-based composition*, for both *interconnection of behaviour* and *containment of knowledge*, and in a domain-independent way.

The minimal set of *primitives* adopted are commonly used elements: `Nodes`, `Ports` and `Connectors` (or semantically equivalent concepts) have been used in several contexts, in one form or another. The real challenge was to identify the minimal set of *constraints* that govern all structural compositions: the lesson learned is that developers tend to be not very aware of such constraints, and the more expert one is in a certain domain, the more obvious and implicit such constraints appear.

The objectives behind this paper are: (i) to separate strictly the structural and behavioural aspects, and (ii) to make *all* structural relationships *explicit* in a formal language, based on *hierarchical hypergraphs*.

The potential benefits of having a common structure are manifold, such as common tools for storing, querying and composing heterogeneous systems, as well as easily create new functionalities or DSLs based on the graph structure. Those benefits related to *reuse* of both *modelling concepts* and *software* is discussed by means of two examples; however, only further adoption of the proposed *NPC4* model can validate the research hypotheses, and this adoption depends strongly on the further development of *tools* that compose the *NPC4* with other DSLs, exploiting the common structure description.

The behaviour attached to the structural primitives always depends on the specific *context* in which various pieces of the knowledge integrated in the system are valid or not. Hence, it is important to have an explicit computer-readable representation of the *structural knowledge contexts* in which a system is contained; most often, there are many overlapping contexts active at the same time. Hence, the hierarchical hypergraph meta meta model is highly relevant to make the step from traditional engineering systems to *knowledge-aware* engineering systems, that is, systems that can *use the knowledge themselves at run-time*.

In the above-mentioned context, the aspect of *composability* of structural models is an important design focus; *NPC4* advocates that extra "features" (such as behaviour or visualisation) should not be added "by inheritance" (that is, by adding attributes or properties to already existing primitives), but "by composition", that is, a *new* DSL is made, that imports already existing DSLs and adds *only the new* relationships and/or properties as *first-class* and *explicit* language primitives.

Although presented in a robotics context, nothing in *NPC4* depends on this specific robotics domain. *NPC4* can also serve the goals of related to other application domains such as the *Internet of Things*. However, the advantages of the *NPC4* meta model pay off most in robotics, because of (i) the large demand for *knowledge-aware* systems, (ii) the online efficiency and (re)configuration flexibility of such robotics systems, and (iii) their need for the online reasoning about—and eventually the online adaptation of—their own structural architectures.

Finally, the authors suggest the *NPC4* language for adoption as an *application-neutral standard*, since standardizing the structural part of components, knowledge, or systems, is a long-overdue step towards higher efficiency and reuse in robotics system modelling design, and in the development of reusable tooling and (meta) algorithms.

Appendix

This section gives further domain specific explanations for each of the graph structures that where listed in Section 1.

- *software architectures*, as in Fig. 1. Typically, each `Node` represents an input-output relationship that has dynamic and time-varying behaviour, while the structure of the interactions (i.e., the *edges* and the `Ports`) does not change over time. Some frameworks offer hierarchical composition (e.g., Simulink [2] or Modelica [49]), at least in the *modelling* part of system design.
- *kinematics and dynamics of actuated mechanical structures*, as in Fig. 2. The joint nodes contain actuator dynamics, and the link nodes contain rigid-body inertia dynamics; the *edges* represent structural connectivity, modelling which actuators and links are exchanging energy, that is, exhibit behaviour. Hierarchy is possible, e.g., a spherical joint can mechanically be realised by a parallel mechanism.
- *Finite State Machines*, as in Fig. 3, model the *discrete* behaviour of a robot control system. That is, what activities must be running in the system in concurrent ways, and based on which events the system must switch its overall behaviour to another set of concurrent activities. The structure of these switches is modelled by the states being connected via so-called "transitions". Structural hierarchy abstracts away how the system reacts to a set of events.

- *probabilistic graphical models* such as Factor Graphs, Fig. 4, *Nodes* represent time-varying ("behavioural") *information* as captured in "random variables"; *edges* represent ("structural") probabilistic relationships which govern the interaction between the random variables in the connected nodes. *Ports* are typically not represented, such that the graphical model does not allow to indicate which of the random variables in each node are involved in each of the relationships represented by edges.
- *control diagrams* and other "data flow" computational models, such as the control scheme of Fig. 5; popular instances are *Simulink* [2] diagrams, or *Bond Graph* [4], [50], [29], [30], [31] models in *20Sim* [28]. The separation of structure and behaviour is similar to the above-mentioned cases of software and kinematic models: nodes represent "dynamics", edges represent exchange of information or energy.
- *knowledge representation networks*, such as the "semantic web" (represented often by the RDF or OWL) or the robotics *KnowRob* [51]. *Nodes* represent facts, data, term, etc., and *edges* represent relationships. RDF and OWL can only represent "triples" relationships; Lisp and Prolog statements have the semantics of *S-expressions*. Surprisingly, none of the mainstream approaches support *hierarchy* as a top-level modelling primitive, although it is needed to give structure to the concept of various "levels of abstraction" in a knowledge representation of a system.

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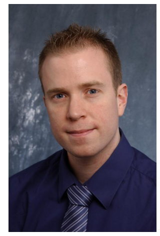

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