Robotic System Specification Methodology Based on Hierarchical Petri Nets

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Plan of presentation

Motivation

- International Federation of Robotics (IFR) anticipates that number of service robots will **triple** in 2023 compared to 2019 [1],
- significant **increase** in the number of new robotic system implementations,
- development of software of a robotic system is a **challenge**,
- tools **facilitating the design** of such systems are in high demand,
- so far, neither a **universal method** for designing robotic systems nor a **universal architecture** for robotic systems has been developed [2].

Motivation II

Approaches to system development usually provide:

- **freedom of choice**,
- software **modules** supplemented with communication mechanisms [3],

However, they do not provide:

- guidelines,
- rules,

on **how to develop** a system that has to execute the required task, which is **evident** for Robot Operating System (ROS) or Open RObot COntrol Software (OROCOS).

The quality of the resulting systems depends primarily on:

- skills,
- experience of the designer.

Motivation III

European SPARC project [4] indicates that the **model-based approach** (i.e. Model Driven Engineering (MDE)) has the **potential to become popular and play an important role in the design of robotic systems**.

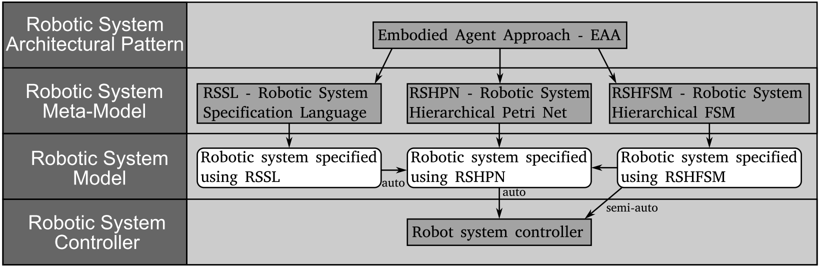
MDE:

- Introduces a **meta-model** and **design patterns**,
- Gives appropriate **balance** between guidance and flexibility ensuring appropriate system structure and operation [4].

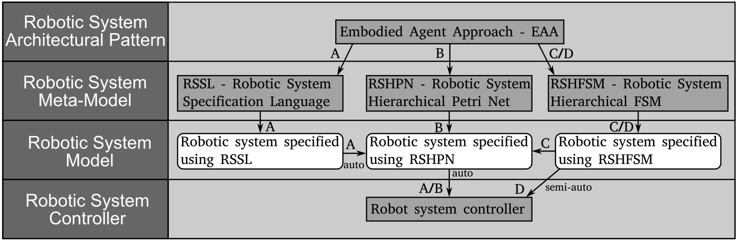
Main goal

Our objective is to develop a **methodology** for designing robotic systems based on **concepts from the field of robotics** and based on the **MDE approach**.

Robotic System Specification Methodology



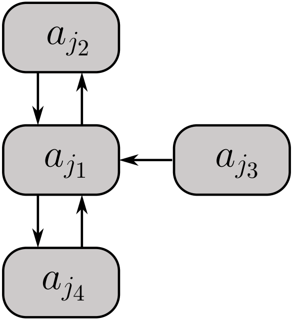
Robotic System Specification Methodology



- A - article in preparation,
- B - Access 2020 [5], ICRA 2019 [6],
- C - Automation 2019 [7],
- D - RoMoCo 2017 [8], JINT 2019 [9], Automation 2018 [10].

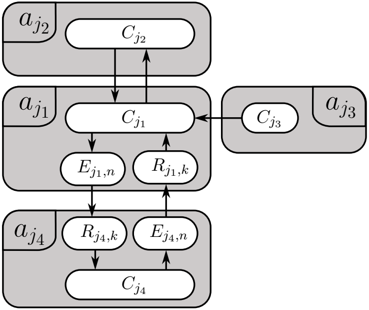
Structure - system decomposition into agents

A)



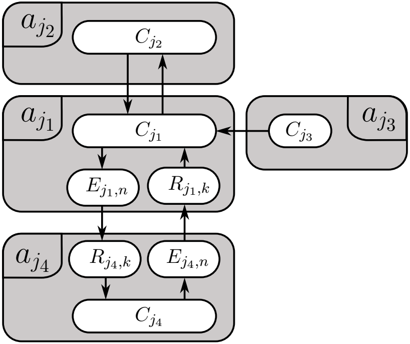
$\Rightarrow$

B)



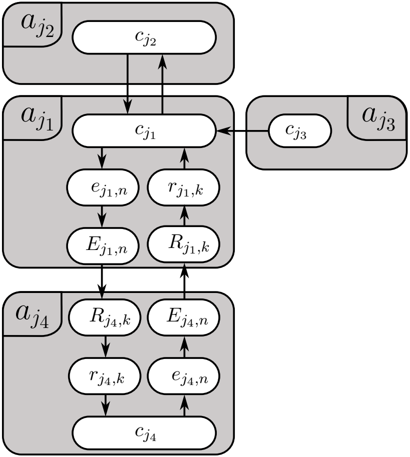
Structure - system decomposition into agents

B)

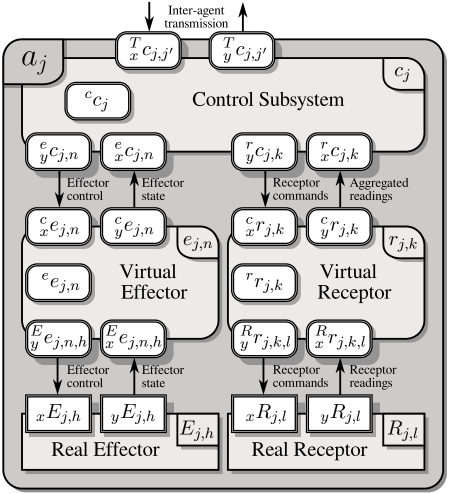


$\Rightarrow$

C)

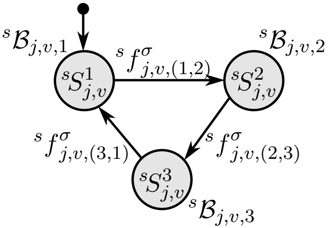


Structure - system decomposition into cooperating agents

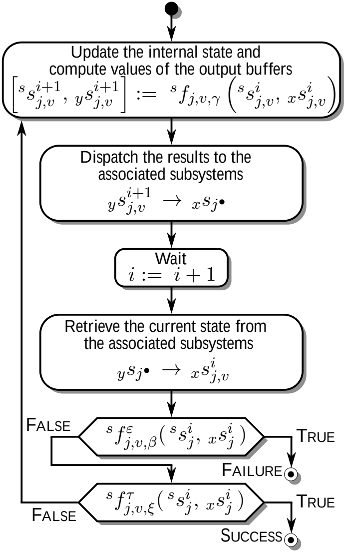


Activity of robotic system $\mathcal{RS}$

- $\mathcal{RS}$ performs a task $\mathcal{T}$,
- $\mathcal{T}$ is composed of tasks $\mathcal{T}_j$ performed by a_j,
- $\mathcal{T}_j$ is composed of tasks $\mathcal{T}_{j,v}$ performed by $s_{j,v}$,
- the execution of task $\mathcal{T}_{j,v}$ involves performing and switching between behaviours ${}^s\mathcal{B}_{j,v,\omega}$,
- subsystem $s_{j,v}$ **switches between behaviours** based on initial condition ${}^sf^{\sigma}_{j,v,\alpha}$.



Activity of behaviour ${}^{s}\mathcal{B}_{j,v,\omega}$



Transition function - decomposition

$$[{}^{s}s^{i+1}_{j,v},\ {}^{s'}_{y}s^{i+1}_{j,v,v'}] := {}^{s}f_{j,v,\gamma}\left({}^{s}s^{i}_{j,v},\ {}^{s'}_{x}s^{i}_{j,v,v'},\ {}^{s''}_{x}s^{i}_{j,v,v''}\right)$$

Canonical decomposition

Decomposition of ${}^{s}f_{j,v,\gamma}$ with respect to the **destination of the calculated data**: i.e. output buffer or internal memory buffer, a partial transition functions are created:

- ${}^{s'}_{y}s^{i+1}_{j,v,v'} := {}^{s,s'}f_{j,v,\gamma,\psi}\left({}^{s}s^{i}_{j,v},\ {}^{s'}_{x}s^{i}_{j,v,v'},\ {}^{s''}_{x}s^{i}_{j,v,v''}\right)$,
- ${}^{s}s^{i+1}_{j,v} := {}^{s,s}f_{j,v,\gamma,\psi'}\left({}^{s}s^{i}_{j,v},\ {}^{s'}_{x}s^{i}_{j,v,v'},\ {}^{s''}_{x}s^{i}_{j,v,v''}\right)$,

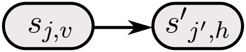
Decomposition by data access

Partial transition function ${}^{s,s'}f_{j,v,\gamma,\psi}$ is decomposed due to the **availability of input data**, an overloaded transition function is created accepting **various combinations** of input buffers.

Communication

- Inter-agent communication (using transmission buffer, and using environment),
- Intra-agent communication

Communication occurs always between a pair of subsystems, e.g. $s_{j,v}$ and $s'_{j',h}$:



Sender acting in mode:

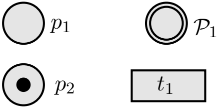
- blocking $\equiv$ B,
- blocking with timeout $\equiv$ BT,
- non-blocking $\equiv$ NB

Receiver acting in mode:

- blocking,
- blocking with timeout,
- non-blocking

For a pair of subsystems 9 different combinations of communication models are possible!

HPN



Transition associated with:

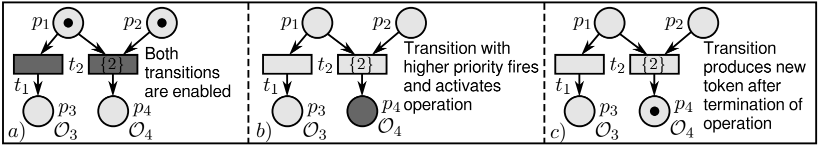
- condition – $\mathcal{C}$,
- priority – $\mathcal{P}r$,
- timeout

Place associated with:

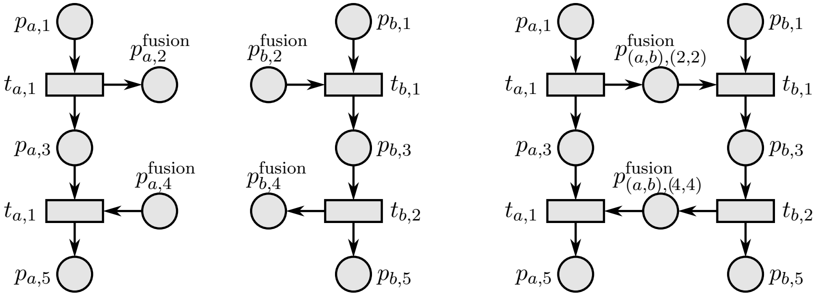
- operation – $\mathcal{O}$,
- number of tokens

Page associated with:

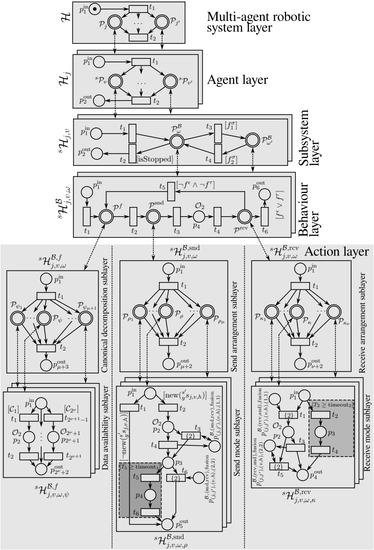
Petri net (HPN)



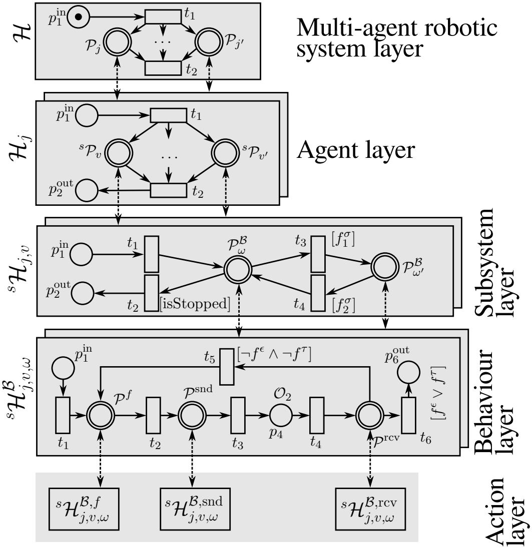
Place fusion



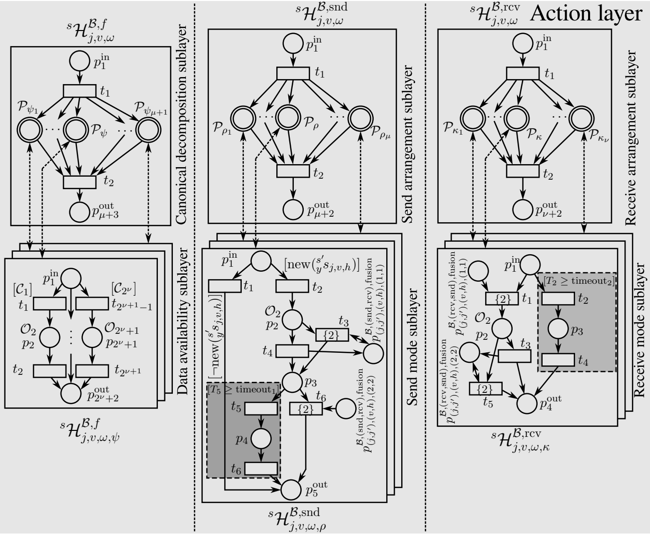
Robotic System HPN (RSHPN) meta-model



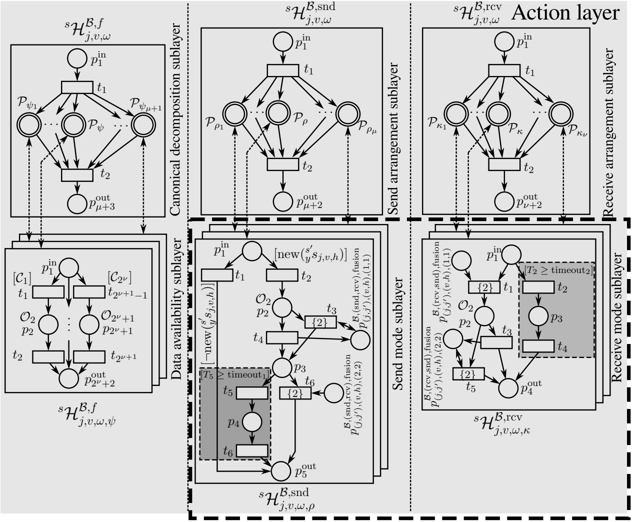
RSHPN modelling a robotic system



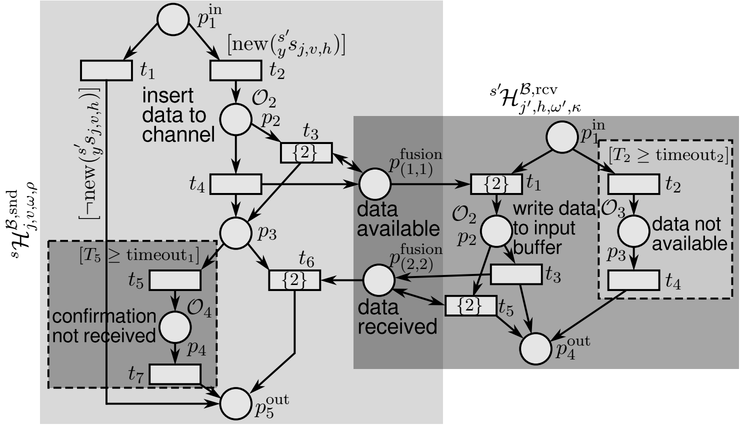
RSHPN - Action layer



Communication model



General communication model



Communication model depends on timeouts

Communication model		Receive: $\text{timeout}_2 = 0$	Receive: $\text{timeout}_2 = \infty$	Receive: $0 < \text{timeout}_2 < \infty$
Send	$\text{timeout}_1 = 0$	NB-NB	NB-B	NB-BT
Send	$\text{timeout}_1 = \infty$	B-NB	B-B	B-BT
Send	$0 < \text{timeout}_1 < \infty$	BT-NB	BT-B	BT-BT

where:

- NB – non-blocking mode,
- B – blocking mode,
- BT – blocking mode with timeout.

RSHPN analysis

RSHPN properties analysis

RSHPN complexity analysis

RSHPN properties analysis - Idea

- decomposition of RSHPN into layers, and panels,
- analysis of Petri nets from panels (reduction methods used),
- analysis of Petri nets associated with communication and nets composed of multiple layers,
- three types of PN: trivial, unchangeable, user defined,

Properties verification:

- 1-boundedness, safety,
- lack of deadlocks,

Analysis methods:

- graphical (for trivial nets),
- reachability graph,
- methods based on place and transition invariants

RSHPN COMPLEXITY ANALYSIS

Complexity depends on number of places/transitions/edges

The higher the complexity, the more difficult/longer it is to develop a Petri net. Also, the greater the error prone.

Number of places/pages in $\mathcal{H}$:

$$\text{places}(\mathcal{H}) = \sum_{a_j \in \hat{a}} \Big(\sum_{s_{j,v} \in \hat{s}_j} |{}^{s}\hat{\mathcal{B}}_{j,v}| \cdot \Big(2^{|{}_{x}\hat{s}_{j,v}|} \cdot \Big(|{}_{x}\hat{s}_{j,v}| + 1 \Big) + 8 \cdot |{}_{x}\hat{s}_{j,v}| + \\ + 10 \cdot |{}_{y}\hat{s}_{j,v}| + 16 \Big) + 3 \cdot |\hat{s}_j| \Big) + 3 \cdot |\hat{a}| + 1 \tag{1}$$

Number of transitions in $\mathcal{H}$:

$$\text{transitions}(\mathcal{H}) = \sum_{a_j \in \hat{a}} \Big(\sum_{s_{j,v} \in \hat{s}_j} \Big(|{}^{s}\hat{\mathcal{B}}_{j,v}| \cdot \Big(\Big(|{}_{y}\hat{s}_{j,v}| + 1 \Big) \Big(2^{|{}_{x}\hat{s}_{j,v}| + 1} \Big) + 4 \cdot |{}_{y}\hat{s}_{j,v}| + \\ + 3 \cdot |{}_{x}\hat{s}_{j,v}| + 10 \Big) + |{}^{s}\hat{f}^{\sigma}_{j,v}| \Big) + 2 \cdot |\hat{s}_j| \Big) + 2 \cdot |\hat{a}| + 2 \tag{2}$$

Number of edges in $\mathcal{H}$:

$$\text{edges}(\mathcal{H}) = \sum_{a_j \in \hat{a}} \Big(\sum_{s_{j,v} \in \hat{s}_j} \Big(|{}^{s}\hat{\mathcal{B}}_{j,v}| \cdot \Big(2^{|{}_{x}\hat{s}_{j,v}| + 2} \cdot \Big(|{}_{y}\hat{s}_{j,v}| + 1 \Big) + 21 \cdot |{}_{y}\hat{s}_{j,v}| + \\ + 16 \cdot |{}_{x}\hat{s}_{j,v}| + 20 \Big) + 2 \cdot |{}^{s}\hat{f}^{\sigma}_{j,v}| \Big) + 6 \cdot |\hat{s}_j| \Big) + 4 \cdot |\hat{a}| + 1 \tag{3}$$

RSHPN complexity analysis

Nr	$\|\hat{a}\|$	$\|\hat{s}_j\|$	$\|{}^s\hat{\mathcal{B}}_{j,v}\|$	$\|{}_x\hat{s}_{j,v}\|$	$\|{}_y\hat{s}_{j,v}\|$	places($\mathcal{H}$)	transitions($\mathcal{H}$)	edges($\mathcal{H}$)	Total
1	1	1	1	1	1	45	32	86	163
2	1	1	1	5	5	125	76	266	467
3	5	1	1	1	1	221	152	426	799
4	5	1	1	5	5	621	372	1326	2319
5	5	5	1	1	1	1041	712	2046	3799
6	5	5	5	1	1	4841	3312	9546	17699
7	5	5	5	5	5	14841	8812	32046	55699

Note:

For system no. 7, 55699 elements must be created!

Conclusion:

RSHPN $\mathcal{H}$ must be generated **automatically**! $\Rightarrow$ RSSL

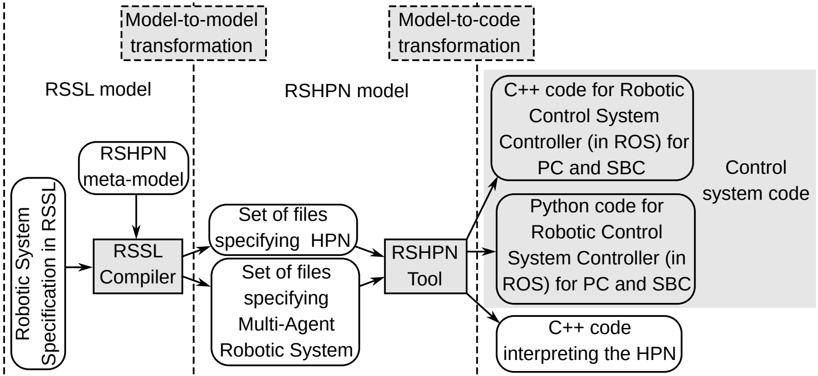
Robotic System Specification Language

- a domain language for specifying multi-agent robotic systems,
- based on concepts derived from robotics, in particular the embodied agent,
- RSSL specifies both the structure and the activity of a robotic system,
- RSSL is specified using a context-free grammar expressed in BNF form.

RSSL enables RSHPN meta-model parameterization

Layer/Sublayer	Parameters
Multi-agent robotic system	$\hat{a}$
Agent	for each $a_j \in \hat{a}$: $\hat{s}_j$
Subsystem	for each $s_{j,v} \in \hat{s}_j$: ${}^{s}\hat{\mathcal{B}}_{j,v}$, ${}^{s}\hat{f}^{\sigma}_{j,v}$, ${}_{y}\hat{s}_{j,v}$, ${}_{x}\hat{s}_{j,v}$ and ${}^{s}\mathcal{T}_{j,v}$
Behaviour	for each ${}^{s}\mathcal{B}_{j,v,\omega} \in {}^{s}\hat{\mathcal{B}}_{j,v}$: ${}^{s}f_{j,v,\gamma}$, ${}^{s}f^{\tau}_{j,v,\xi}$, ${}^{s}f^{\epsilon}_{j,v,\beta}$
Canonical decomposition	for each ${}^{s}f_{j,v,\gamma}$: ${}^{s}\hat{f}_{j,v,\gamma}$
Data availability	for each ${}^{s}f_{j,v,\gamma,\psi} \in {}^{s}\hat{f}_{j,v,\gamma}$: ${}^{s}\hat{f}_{j,v,\gamma,\psi}$
Send arrangement	for each ${}^{s}\mathcal{B}_{j,v,\omega} \in {}^{s}\hat{\mathcal{B}}_{j,v}$: sending_order
Send mode	for each ${}^{s}_{y}s_{j,v,v'} \in {}_{y}\hat{s}_{j,v}$ while executing ${}^{s}\mathcal{B}_{j,v,\omega} \in {}^{s}\hat{\mathcal{B}}_{j,v}$: timeout_1
Receive arrangement	for each ${}^{s}\mathcal{B}_{j,v,\omega} \in {}^{s}\hat{\mathcal{B}}_{j,v}$: receiving_order
Receive mode	for each ${}^{s}_{x}s_{j,v,v'} \in {}_{x}\hat{s}_{j,v}$ while executing ${}^{s}\mathcal{B}_{j,v,\omega} \in {}^{s}\hat{\mathcal{B}}_{j,v}$: timeout_2

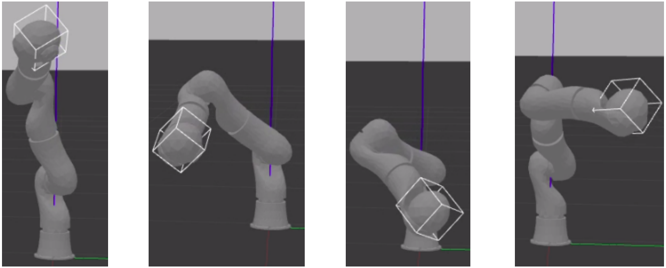
Translation



Experiments

- LWR4+ manipulator (specified from scratch),
- Table-tennis ball collecting robot (developed from scratch),
- Velma robot transferring balls (extended based on existing controller)

LWR4+ manipulator



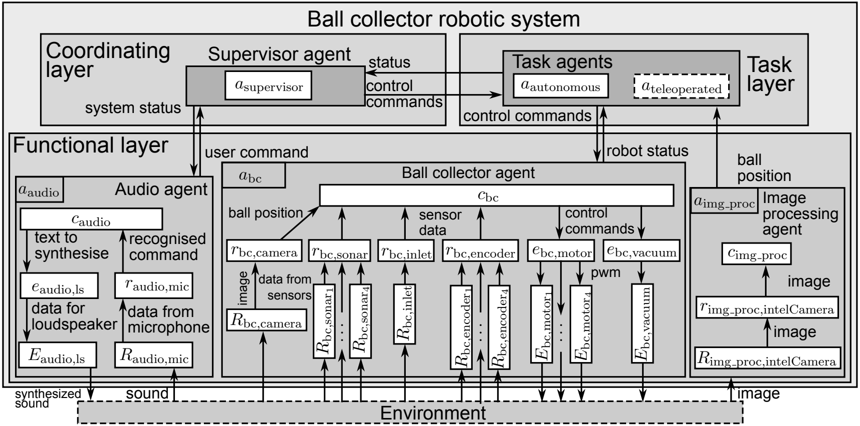
(a) (b) (c) (d)

Simulated LWR4+ manipulator with 7 degrees of freedom controlled using impedance control. Its end-effector moves along a circular trajectory (only its Cartesian position is controlled).

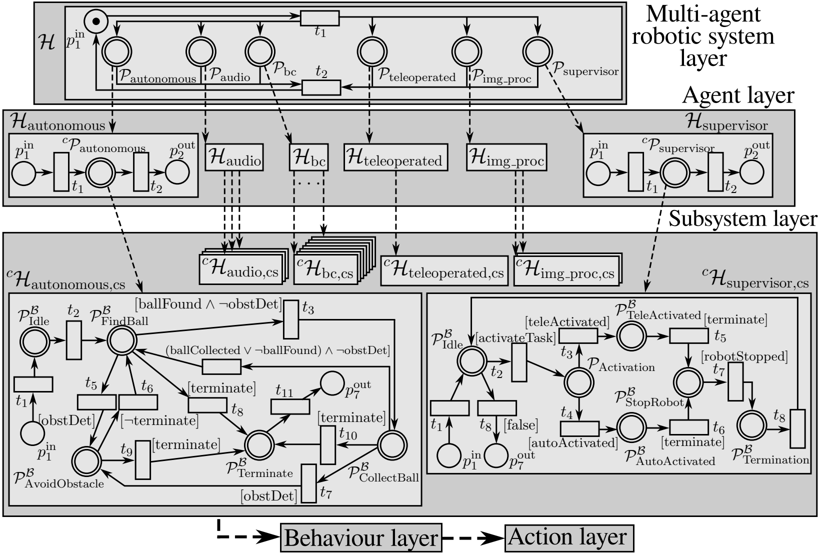
Table-tennis ball collecting robot

Ball collecting robot and the environment; camera images: (c) Raspberry Pi, (d) Intel Realsense D435; detected balls (in rectangles), closest ball (in circle).

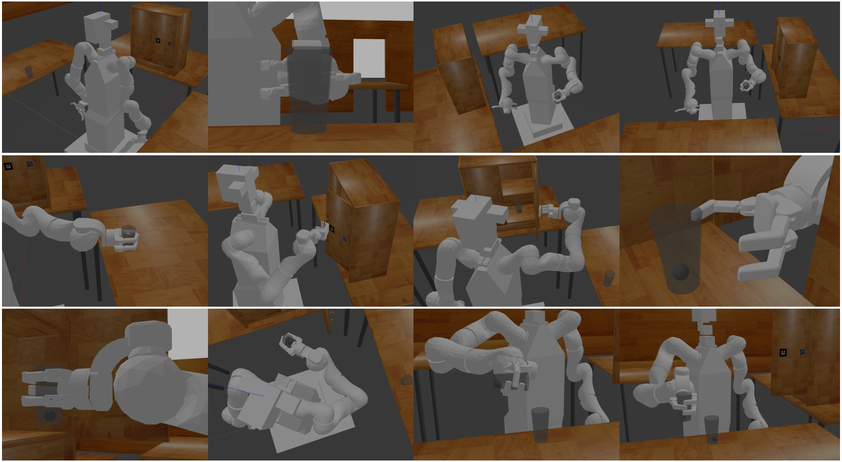
Ball-collecting robot – Structure



Ball-collecting robot – Activity

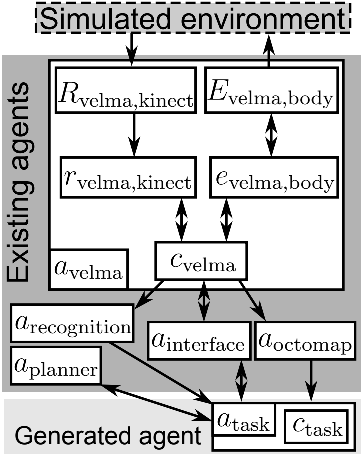


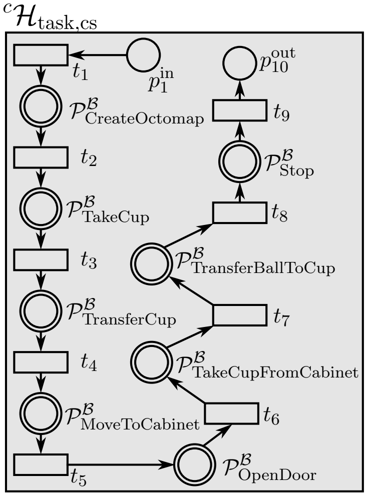
Velma robot transferring balls



Transfer of a ball from the cup located in the cabinet to the cup initially relocated from one table to the other.

Balls transfer – Structure and activity



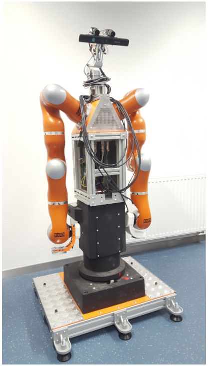


Conclusions

- RSSM methodology based on MDE has been proposed,
- a parameterized RSHPN meta-model was proposed,
- RSHPN Tool for RSHPN creation was developed,
- RSHPN network analysis was performed,
- RSSL domain language was developed for the specification of robotic systems,
- RSHPN meta-model and RSSL approaches were verified

Perspectives on continuing research

- RSHPN extension of the meta-model (e.g., time considerations),
- time-related analysis,
- generation of controller code for OROCOS,
- verification of the approach on a real Velma robot



Thank you for your attention!

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